PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 12(sp1): 01–15
https://doi.org/10.14719/pst.4115

HORIZON
e-Publishing Group
HePG

REVIEW ARTICLE

Unveiling the nutraceutical properties and functional attributes of sorghum-Comprehensive review

Shanalin J[1], R Chandirakala[1]*, N Manikanda Boopathi[2], K Chandrakumar[3], V Veeranan Arun Giridhari[4] & S Sivakumar[5]

[1]Department of Genetics and Plant Breeding, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[2]Department of Plant Biotechnology, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[3]Department of Renewable Energy Engineering, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[4]Department of Post-Harvest Technology, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[5]Department of Millets, Center for Plant Breeding and Genetics, Tamil Nadu Agricultural University, Coimbatore 641 003, India

*Email: chandirakala2009@gmail.com

OPEN ACCESS

ARTICLE HISTORY
Received: 15 June 2024
Accepted: 13 January 2025
Available online
Version 1.0 : 11 February 2025

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Shanalin J, Chandirakala R, Boopathi NM, Chandrakumar K, Giridhari VVA, Sivakumar S. Unveiling the nutraceutical properties and functional attributes of sorghum - Comprehensive review. Plant Science Today.2025;12(sp1):01-15.
https://doi.org/10.14719/pst.4115

Abstract

Sorghum (*Sorghum bicolor* L.) is one of the most significant yet underutilized staple crops in the world. It contains high levels of dietary fiber, resistant starch and essential health-beneficial bioactive compounds, including phenolics, vitamins and minerals, making it a valuable component of a balanced diet. The bioactive profiles of sorghum are exceptionally unique, more abundant and more diverse than those of other common cereal grains. Sorghum contains phenolic acids, condensed tannins and 3-deoxyanthocyanidins as its primary phenolic constituents. Consumption of sorghum whole grain may enhance gut health and lower the risk of chronic illnesses, as studies have demonstrated the strong antioxidant activity of sorghum's phenolic components *in vitro*. Additionally, condensed tannins, 3-deoxyanthocyanidins and phenolic compounds are essential contributors to its health benefits. Recently, sorghum grain has been increasingly used to develop functional foods and beverages, as well as an ingredient in other food products. The objective of this review is to provide a comprehensive understanding of the nutritional composition and functional properties of sorghum, along with its related health benefits, to improve health outcomes and overall well-being.

Keywords

kafirin; nutritional profile; phenolic substances; phytochemical constituents; sorghum; therapeutic advantages

Introduction

Globally, ensuring nutritional security is essential for maintaining public health, fostering economic development and promoting social stability. In India, a significant portion of the population faces malnutrition or undernourishment, hindering both physical and mental growth. The prevalence of undernutrition in India stands at 16.3%, with alarming rates of stunting (30.9%), underweight children (33.4%) and childhood obesity (3.8%) (1). Improving food security can significantly impact poverty reduction efforts by providing individuals with access to affordable and nutritious food, thereby enabling better financial management, reducing healthcare expenses and enhancing overall quality of life. In 2022, the World

Health Organization estimated that 149 million children under the age of five were stunted (too short for their age); 45 million were anticipated to be wasted, or too thin for their height and 37 million were obese (2). Approximately 74% of Indians lacked access to a nutritious food and 39% did not consume a diet high enough in nutrients. More than 1.6 million children are predicted to experience malnutrition by 2024, according to a warning from the World Food Programme (WFP) (3).

Thus, sorghum, a gluten-free cereal, is a cornerstone of sustenance for many communities in the semi-arid tropical regions and is acknowledged as one of the notable crop species within the Poaceae family across Africa, Asia and Latin America (4). Following maize, rice, wheat and barley, cultivated sorghum is ranked fifth among the cereal crops globally (5). Over 35% of sorghum is cultivated specifically as food, while the remainder is primarily used for industrial goods, alcohol and animal feed (6). Every year, sorghum breeders develop numerous improved sorghum varieties suited for tropical and semi-arid climates. The increasing prevalence of sorghum in developing nations can be attributed to concerted national efforts to enhance processing and industrial applications, in conjunction with the rising populations in these regions (7). A well-known feature of sorghum is its high agronomic productivity and its capacity to grow under a variety of conditions, such as deficit water and high temperatures, salinity, barren soils and high altitudes. This adaptability is due to its well-established root system, high root-to-leaf ratio and wax-coated foliage, which can roll in response to external stimuli or threats (8). Sorghum remains a preferred choice as it is gluten-free, contains resistant starch, is an excellent source of minerals and comprises a collection of bioactive phenolic compounds. Sorghum surpasses other key cereal crops in its concentration of phenolic compounds, showcasing a broad range of bioactive constituents that are especially pronounced (9).

Sorghum grains containing bioactive chemicals boost the gut microbiota and exhibit a varied range of biological activities, including anti-inflammatory, antioxidant, antithrombotic and antidiabetic qualities. Whole grains, including millets, are indispensable for achieving good physical fitness and overall health, as they provide substantial quantities of essential energy and dietary fiber (10, 11). Consuming such grains can reduce the risk of various cancers, improve blood glucose balance, aid in body weight management and lowers the risks of cardiovascular and diabetes by 20% to 30% (12-14).

Reports have substantiated that the bioactive compounds inherent in grains exhibit a spectrum of functional effects, including antibacterial, anti-inflammatory and antioxidant properties, all of which contribute mitigating various health concerns (15). To further enhance its contribution to nutrition security, sorghum can be improved through selective breeding for enhanced nutritional traits, processing techniques to increase bioavailability, fortification and education initiatives to promote its consumption. By employing these methods, sorghum can play a significant role in addressing global nutritional challenges and ensuring access to nutritious food for all. This review provides a summary of the bioactive chemicals and functional properties present in sorghum, along with the health advantages they offer as a result of their dietary uses and biological potential.

Grain morphology of sorghum

Pericarp

The pericarp, the outermost structural element of the caryopsis, consists of three sublayers: the epicarp, mesocarp and endocarp. The epicarp is further subdivided into hypodermic and epidermic portions. The epidermis of the caryopsis is composed of thin, elongated, rectangular cells with a cutin layer on the outer surface. The outer layer often contains a pigment. Phytochemical levels, such as anthocyanins, carotenoids and condensed tannins are reflected in the different pericarp colors. These colored pigments have potential therapeutic properties and offer a variety of health benefits. Anthocyanidins and anthocyanins exhibit antioxidative and antibacterial properties, enhancing visual and neurological health and protecting against a variety of noncommunicable diseases, as shown by scientific research conducted on cell culture, animal models and human clinical trials. The hypodermic layer, with a thickness ranging from one to three cellular layers, consist of significantly fewer cells than the epidermis. The mesocarp, the central section of the pericarp, is its densest portion, though its thickness varies greatly among genotypes. The endocarp, the deepest sublayer of the pericarp, is framed by cross cells and an outer layer of tube cells. It facilitates moisture transport into the kernel (Fig. 1) (16).

Outer seed coat

The testa, or seed-coat, is located immediately beneath the endocarp. The testa exhibits notable stages of pigmentation in certain genotypes of sorghum. Both hue and pigmentation are inherited traits. The thickness of the testa layer varies; it is narrow in the embryo section and thick near the kernel's crown. The testa is present in certain genotypes but absent or only partially in others (16).

Endosperm

The fundamental portion of sorghum constitutes the endosperm, which function as a vital storage structure. It includes the outermost corneous and floury portions, plus an aleurone layer. The aleurone is a single layer of cells that sits just underneath the testa, or seed coat (Fig. 1). Minerals, oil, B-complex vitamins and several hydrolyzing enzymes are plentiful in these aleurone cells. Long, rectangular cells that are tightly packed and include protein bodies and starch granules embedded in the protein matrix are characterize the peripheral endosperm. Therefore, unless the protein linked to it is also reduced, the starch in these cells is not readily accessible for enzyme digestion (17). Protein-starch interactions in sorghum, especially the dense kafirin matrix and tannins,

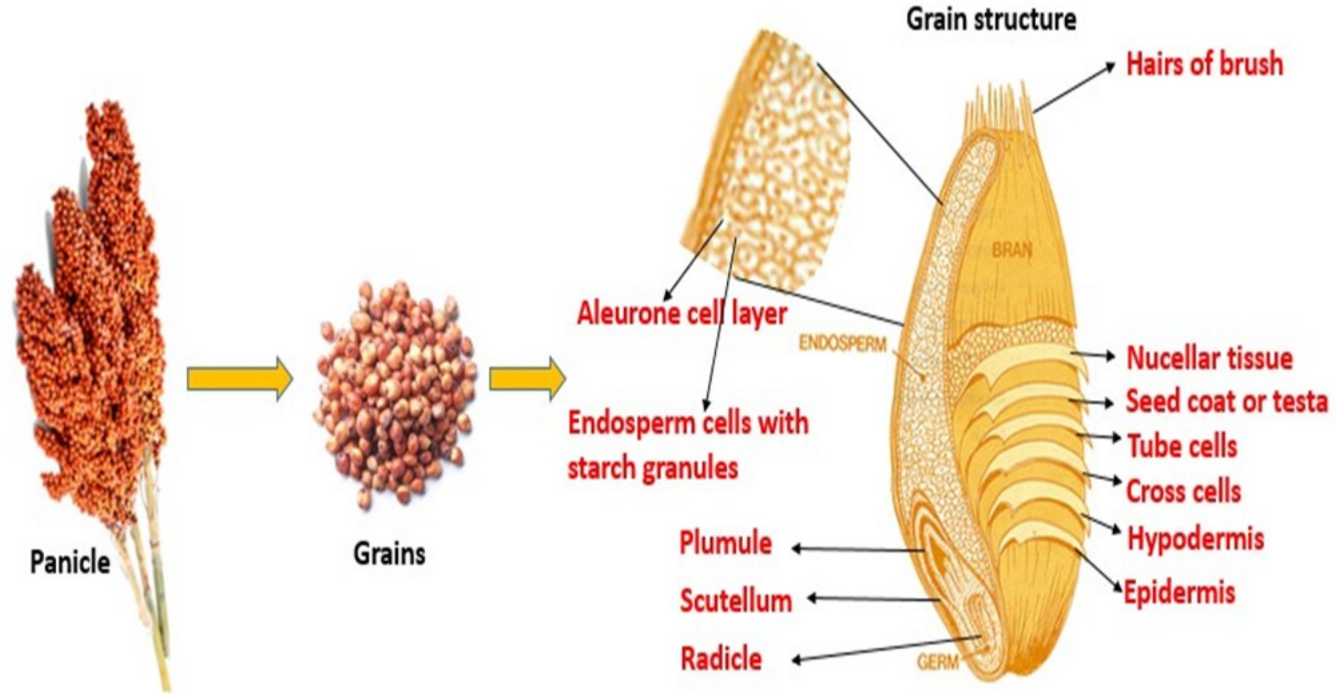

Fig. 1. Structure of sorghum grain.

reduce starch digestibility and nutrient availability compared to more digestible grains like maize and wheat. The main protein in the kernel is composed of alcohol-soluble prolamins, which form the protein bodies and alkali-soluble glutelin, which constitute the general protein framework. The spherical protein structures observed in the sorghum endosperm vary in size both between species and within a kernel. In sorghum, the number of protein bodies decreases as the starch concentration increases from the periphery to the center, where the floury endosperm is located. The protein domains of sorghum, are characterized by the presence of various enzymatic agents such as proteases, 3-glucosidases, 3-galactosidase and phosphatases (18). Red sorghum (IS 11315) has high tannins, which reduce digestibility but increase antioxidants; white sorghum (IS 8525) is easier to process due to low tannins and better nutrient bioavailability; high-lysine sorghum (P721Q) offers enhanced protein quality and waxy sorghum (BRS 511) has improved starch gelatinization for processed foods. Complementing these enzymatic agents, sorghum protein bodies also contain essential minerals, including magnesium, calcium, potassium and phosphorus. The key factors influencing sorghum processing and its nutritional value is grain texture. In sorghum, the kernel texture ranges from delicate endosperm to all corneous, extremely hard, or vitreous endosperm. When decorticated, hard endosperm sorghum produces more full grains and fewer broken grains than softer endosperm. Corneous flours generate more flour during dry milling than soft flours do. Nonetheless, soft-endosperm genotypes generate more starch after wet milling. Varieties with a larger percentage of crystalline endosperm are preferable for cooking concentrated porridge and these cultivars are also appropriate for popping (19). Soft-endosperm sorghum flour is widely desired for making bread, whether it is fermented or not.

Germ

The scutellum and the embryonic axis are the two primary components of the germ. The scutellum acts as storage tissue for minerals, proteins, lipids and enzymes (Fig. 2). The fatty acids present in polyunsaturated oil are similar to those in maize oil (20).

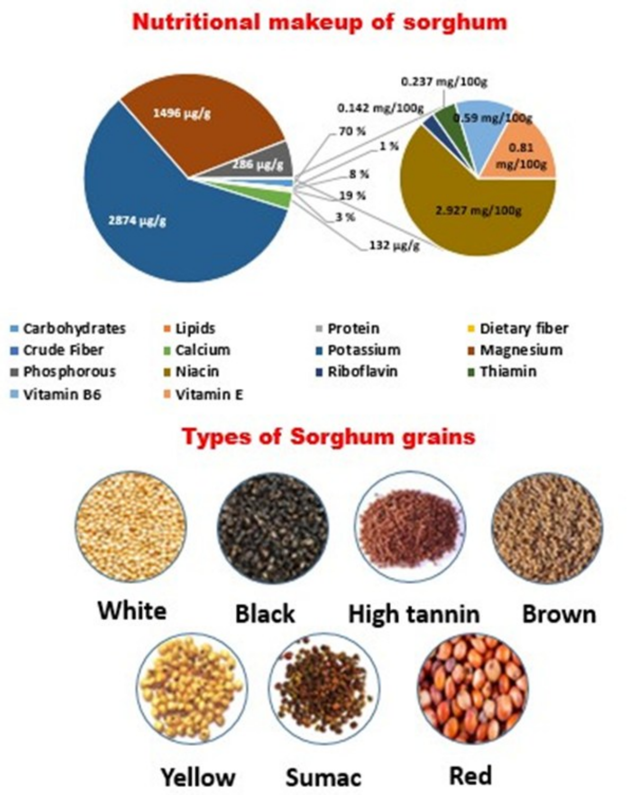

Fig. 2. Nutritional makeup and types of sorghum.

Nutraceutical profiling of sorghum

Highly esteemed for its exceptional nutritional content, sorghum has become a significant food crop in Africa and India, as well as a vital source of animals feed in wealthier nations. Sorghum contains approximately 70%–80% carbohydrates, 8%–18% protein, 19% dietary fibre, 3% crude fibre, 1-5% lipids and various vitamins and minerals (Table 1).

Table 1. The nutritional makeup of sorghum (85)

Macronutrients	Content (%)	NRVs-R[a] (mg/100g)
Carbohydrates	70–80	-
Lipids	1–5	-
Protein	8–18	-
Dietary fiber	19	-
Crude Fiber	3	-
Mineral	**Content (µg/g)**	**NRVs-R[a] (mg/100g)**
Calcium	132	1000
Potassium	2874	-
Magnesium	1496	310
Phosphorous	286	700
Vitamins	**Content (mg/100g)**	**NRVs-R[a] (mg/100g)**
Niacin	2.927	15
Riboflavin	0.142	1.2
Thiamin	0.237	1.2
Vitamin B6	0.590	1.3
Vitamin E	0.810	9

[a] **NRVs-R, Nutrients Reference Values- Requirements**

Carbohydrate

The carbohydrate in sorghum is starch, which is stored in the endosperm as granules. The starch content varies greatly, ranging from 32.1 to 72.5 g per 100 g of grain (21). The two primary constituents of sorghum starch are amylose and amylopectin; however, some waxy sorghums may contain little or no amylose (22). Sorghum has the lowest starch digestibility among cereals, due to the enormous amount of resistant and slowly digesting starch, as well as the strong interactions between endosperm proteins, condensed tannins and starch granules (23). The strong interactions between proteins (mainly kafirins) and starch granules in sorghum significantly reduce the digestibility of its starch, resulting in a lower glycemic index (GI) compared to more easily digestible grains such as wheat, rice, or maize. This slower breakdown of starch leads to a more gradual release of glucose into the bloodstream, preventing sharp blood sugar spikes and providing more sustained energy. For people with diabetes or those concerned with metabolic health, this lower GI can aid in better blood sugar management, improve insulin sensitivity and reducing the risk of hyperglycemia. Additionally, the slow digestion can increase satiety, making sorghum useful for weight management and overall metabolic balance. Sorghum is high in fibre, which helps lower cholesterol, improve blood sugar regulation and facilitate digestion. The non-starch carbohydrate in sorghum is soluble fibres (10% to 25%) and insoluble fibres (75% to 90%), which are found in the cell walls of the pericarp and endosperm, and constituting nearly 6 to 15 g per 100 g of grain (24). The main components of sorghum's non-starch carbohydrates are arabinoxylans and β-glucans. It has been demonstrated that arabinoxylans, or pentosans, in grains can alter the water balance, the structural characteristics of dough and the retrogradation of starch (13). These are polysaccharides with arabinose residues branching off a xylan backbone. Research has been conducted on the structural properties and carbohydrate composition of arabinoxylans derived from sorghum, which are suitable for making roti (22). P-coumaric and ferulic acids, two significant phenolic acids in sorghum, are bound in the arabinoxylans, which are essentially glucuronoarabinoxylans (25). Sorghum flour is comparable to wheat flour in terms of starch content; however, it contains substantially less amylase (40–50%) and amylolytic (10%) enzyme activity.

Hemicellulose

Panicles, sorghum flour, sorghum bran and sorghum stalk all contain various forms of hemicelluloses. Depending on the tissue and organ type, different plant species have different hemicellulose compositions and structures (26). A prior study found that the water-extractable portion of sorghum flour included traces of xyloglucan and D-glucans (1, 3) and (1, 4). However, in the water-insoluble cell wall material, glucose was observed to be co-extracted and associated with arabinoxylan. Glucoarabinoxylan (GAX) makes up the hemicellulose in sorghum flour due to its high glucose content. Sorghum has L-arabino-(4-O-methyl -Dglucurono)-D-xylans in its stalks (26). A framework made up of 1-4, D-xylopyranose residues, where certain xylose units have single arabinofuranose units coupled to their O-3, or both their O-2 and O-3. Other compounds, either individually or in chains, are connected to the xylose and arabinose residues at O-2. These structures include glucuronic acid and 4-O-methyl glucuronic acid. Xyloglucans are versatile substances with wide-ranging application in the food and non-food sectors. They are employed as binding and adhesive agents in the textile sector, as well as thickening, gelling and stabilizing agents in food items (27). Prior studies have examined the physicochemical qualities of xyloglucans concerning food applications, such as their flow properties, water holding ability and resistance to heat, salt and a range of pH levels (27). Conversely, glucans have already gained widespread recognition for their beneficial special effects on health, such as their capacity to reduce serum cholesterol and modulate insulin and postprandial blood glucose responses. Moreover, food and beverage products worldwide have incorporated the physical characteristics of glucans, such as their water solubility, viscosity and gelation. Due to its soothing, moisturizing, and anti-irritant qualities, glucan is preferred in cosmetics and other personal care products, in addition to the food and pharmaceutical sectors.

Protein

The sorghum protein can generally be classified as non-prolamin proteins (globulins, glutelins and albumins) or prolamin proteins (kafirins). These kafirins found in sorghum make up 70% of the overall protein content in the whole grain and serve as the primary form of protein storage within the grain (28). The endosperm stores these hydrophobic kafirin proteins in tightly coiled protein structures known as α-, β-, γ- and δ-kafirin, which are categorised based on molecular weight (28). The potential of sorghum kafirin for a wide range of uses has made it a topic of significant attention in recentyears. Extensive research has examined sorghum kafirin, covering its extraction, modification and application as a gluten-free ingredient in baked goods, films and coatings. Kafirins, the main storage proteins in sorghum, form tight protein-starch matrices that reduce dough elasticity and hinder the formation of bread-like products. They also encapsulate starch, decreasing its digestibility and leading to a slower release of glucose. The hydrophobic nature of kafirins impairs water absorption and gelatinization, resulting in firmer textures in sorghum-based foods. Additionally, their rigid structure challenges processing techniques such as fermentation and extrusion, limiting the potential for light, airy products. However, processing strategies, such as protein modification can help improve these functional properties. It is also being studied for its potential use in microparticles for supplement and medication delivery. Kafirins exhibit a high level of polymerization and extensive disulfide bridges, which make them resistant to enzymatic digestion in the intestinal tract and found to have a strong relation with tannins. Based on their molecular weight and solubility, sorghum kafirins can be divided into three primary classes: α, ß, and γ. The amounts of α -kafirin, ß-kafirin, and γ-kafirin in the endosperm vary from floury to vitreous (Fig. 3) (28). Glutamic acid is plentiful in α-kafirins, which have a molecular weight of 22–25 kDa. Methionine and cysteine, two amino acids that contain sulphur and may exist in both monomeric and polymeric forms, are more abundant in ß-kafirins, which have a molecular weight of about 18 kDa. Proline, cysteine and histidine are abundant in γ-kafirins, which have a molecular weight of about 20 kDa. These subunits exist as polymers and oligomers. ß and γ-kafirins form strongly cross-linked disulfide linkages, both intramoleculary and between molecules (28).

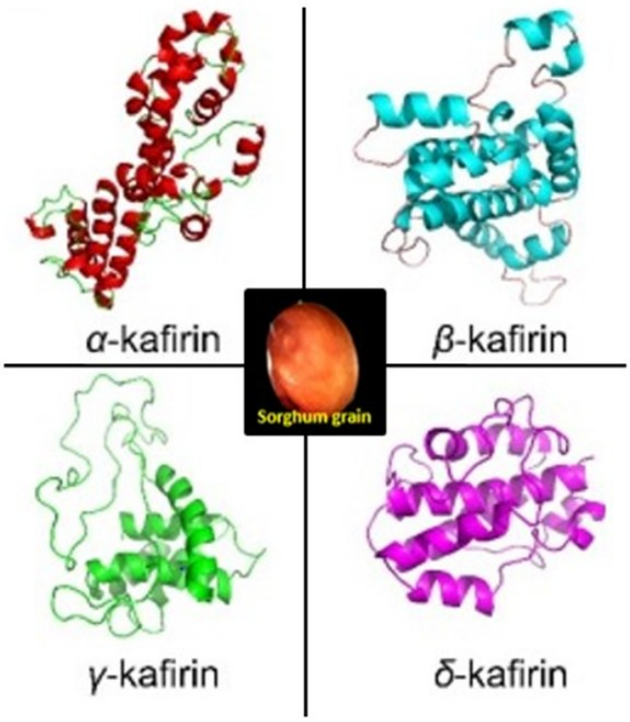

Fig. 3. Types of Kafirin proteins (100).

Amino acid content of sorghum

Sorghum typically contains high levels of glutamic acid, leucine, alanine, proline and aspartic acid among its amino acids (29). From a human nutrition standpoint, lysine and threonine are the most deficient amino acids in sorghum proteins. Lysine content in sorghum meets approximately 40% of the daily recommended intake for infants (30). Transgenesis of the HT12 gene produced lysine-rich sorghum germplasm, enhancing the nutritional value of sorghum grain (31). Additionally, 206 sorghum mutant lines were analyzed for total protein content and 23 amino acids, including 19 protein-bound and 4 non-protein amino acids (32). Variations in the ratios of essential and non-essential amino acids were observed among these lines, with total protein content approximately double that of the wild-type (BTx623) (Table 2).

Vitamins and minerals

Sorghum is a valuable source of minerals, particularly phosphorus (P), which is the most prevalent substance in sorghum kernels (Table 3). However, it is not uniformly distributed and is mainly concentrated in the germ and seed coat. Low extraction rates resulted in a reduction of minerals, including phosphorus, iron, zinc, and copper in milled sorghum flour (33). However, these investigations further demonstrated that pearled grain had greater *in vitro* iron availability, as determined by the ionizable iron as percentage of total iron. Because the hull contains significant amounts of phytate, which binds iron and several other minerals and renders them unavailable to

Table 2. The amino acid content and their daily adult recommendations in sorghum

Amino acid	Sorghum (g/100g protein)[a]	FAO/WHO/UNU adults' recommendations
Essential		
Histidine	2.6	1.5
Isoleucine	4.0	3.0
Leucine	13.1	5.9
Lysine	2.6	4.5
Methionine	1.7	1.6
Cysteine	1.4	0.6
Phenylalanine	4.4	1.9
Tyrosine	3.3	-
Threonine	3.5	2.3
Valine	5.6	3.9
Non-essential		
Alanine	8.8	-
Arginine	3.6	-
Aspartic	7.4	-
Glutamic	19.7	-
Glycine	4.1	-
Proline	8.8	-
Serine	3.9	-

[a] (86)
[b] (87).

Table 3. Minerals and vitamins content in sorghum (88)

Minerals	
Major	**mg/100g dwb[a]**
Ca	30
Cl	52
K	277
Mg	148
Na	11
P	305
S	116
Si	200
Minor	**mg/100g dwb[a]**
Cu	1.0
Fe	7.0
Mn	2.6
Zn	3.0
Vitamins	
Major	**mg/g dwb[a]**
Thiamin	0.46
Riboflavin	0.15
Niacin	4.84
Pyridoxine	0.59
Pantothenic acid	1.25
Biotin	0.02
Folacin	0.02
Carotenes (mg/Kg)	29.0
Minor	**mg/g dwb[a]**
Vitamin E (mg/Kg)	12.0

Source: (88)

the body, dehulling increases the availability of iron. Mechanically dehulled sorghum gruels have a higher proportion of soluble and ionizable iron compared to conventionally ground grains (34). Mechanical milling removes phytate-rich hulls, while soaking before dehulling improves phytate breakdown and iron availability.

In experiments with Indian women, iron absorption was higher from tannin-free sorghum cultivars than form high-tannin cultivars (35). Grain pearling also improved iron absorption from sorghum cultivars, with and without high tannin content. The study evaluated iron bioavailability in individuals consuming diets containing varying levels of tannin, phytate and phosphorus. Iron absorption from low- and high-tannin sorghum was similar in healthy individuals but notably lower in anaemic patients when consuming high-tannin sorghum. However, differences in iron absorption disappeared when the phytate contents of the two sorghum meals were equivalent (36).

Sorghum - Functional characteristics

Both structural carbohydrates (glucose, cellulose, hemicelluloses) and non-structural carbohydrates (starch) are present in sorghum grain. Starch is the main non-structural carbohydrate that supplies most of the energy needed for germination. Starch, which is made up of straight-linked amylose chains (glucose units held together by α-1,4 glycosidic bonds) and amylopectin (glucose units held together by α-1,4 glycosidic bonds with additional branching *via* α-1,6 glycosidic linkages), makes up between 50 and 75 percent of the total grain weight of sorghum. Similar to other cereal grains, sorghum grain contains a similar comparable proportion of starch. Generally, it has a lower starch digestibility than maize; moreover, its strong phytochemical content, especially tannins, can block the enzymatic hydrolysis of starch (37) (Table 4). Consequently, it has been a suggested that sorghum might be a beneficial meal for managing obesity and diabetes. Sorghum also contains more fibre content than any other cereal, with the exception of barley. Sorghum has a lower protein content than wheat, barley and maize, but a higher protein content than brown rice and it remains gluten-free (38). Several phytochemicals found in sorghum, including tannins, policosanols, plant sterols, and phenolic compounds, are either essential cellular constituents or secondary metabolites of the plant. These elements are regarded as beneficial for human health (38). Of all the cereals, sorghum has the highest tannin content. Certain sorghum genotypes have a high phenolic and tannin content, which is linked to strong phenolic-starch interactions and *in vivo* enzyme inhibition. These interactions decrease the digestibility of starch, increase resistant starch and reduce the glycemic index (GI) of food (37). Protein, phenolic, flavonoid, resistant starch and dietary fiber levels play significant roles in reducing the glycemic index of starchy foods. Sorghum exhibits the lowest glycemic index (GI) at 32, while barley, rice, waxy rice, and maize have GIs of 67, 79, 48 and 40, respectively (39).

Characteristics of colored sorghum

The pericarp of black sorghum, a genetic variation of red sorghum, becomes black when exposed to sunlight during maturation, while red sorghum contains modest quantities of phenolic compounds but no tannins. The pericarp of black sorghum is primarily where substantial amounts of phenolic chemicals, specifically 3-deoxyanthocyanidins, are present (40). On the other hand, the colored testa and higher condensed tannin levels are characteristics of brown sorghum, also known as tannin sorghum (6). Black and red sorghums both contain 3-

Table 4. Starch composition of sorghum with other cereals

Component	Sorghum	Maize (Corn)	Wheat
Total Starch (%)	68-75	70-73	60-70
Amylose Content (%)	22-32	24-30	25-28
Amylopectin Content (%)	68-78	70-76	72-75
Resistant Starch (%)	3-5	1-2	2-3
Granule Size (µm)	15-20	10-20	2-35
Gelatinization Temp. (°C)	68-77	62-72	58-64
Digestibility	Lower than maize and wheat	High	High
Starch Type	High amylose starch	High amylopectin starch	Intermediate

deoxyanthocyanidins, which have strong stimulating effects on NQO activity and are essential in the fight against oxidative damage (41). Black sorghum contains higher levels of 3-deoxyanthocyanidins, resulting in darker pigmentation, stronger antioxidant properties and greater resistance to environmental stress compared to red sorghum. The major chemicals in black sorghum, luteolinidin and apigeninidin, provide it with great UV protection and insect resistance. Although red sorghum still contains a significant amount of these anthocyanins, it is less antioxidant-active and has a paler red color. Health advantages, such as anti-inflammatory and cardiovascular protection, are more prominent in black sorghum due to its increased anthocyanin concentration. Both varieties serve different purposes; red sorghum is typically used in traditional recipes, while black sorghum is frequently preferred for functional foods. Condensed tannins from sorghum, which have been shown to be strong antioxidants *in vitro,* may also function as "sinks" for free radicals in the gastrointestinal system (42). Furthermore, pro-inflammatory activity and mouse ear edema are significantly inhibited by phenolic extracts from sorghum bran, particularly from black sorghum (43). While white and red sorghums are typically used in Africa to make low-alcohol beers, red sorghum has historical relevance in East Asia for making high-alcohol spirits (44). Recent research on sorghum has indicated a variety of flavors and possible health advantages when used in grain tea drinks (45). Red sorghum's increased phenolic content and antioxidant activity have been found to improve health outcomes when added to bread and pasta (46).

Bio-active compounds in sorghum

Bioactive chemicals, primarily found in bran and distributed throughout the endosperm, are essential components that promote health and prevent disease. These may include non-nutrients, such as polyphenols and carotenoids as well as vitamins like vitamins B, D, E and K (Fig. 4). Table 5 showed the main trace elements with antioxidant activity, zinc, copper and manganese aid in scavenging free-radicals and reducing their deleterious effects (47-49).

Phenolic compounds

A subclass of polyphenols, phenolic acids are organic compounds that include p-coumaric acid, protocatechuic acid, ferulic acid, and others. Sorghum has a more diverse phenolic chemical profile and greater concentration of phenolic compounds compared to other cereals. All varieties of sorghum include phenolic compounds, which are the main bioactive ingredients in this grain. Sorghum primarily contains ferulic acid as its main phenolic acid, similar to small-grained cereal grains. Additionally, sorghum grain hosts flavonoids capable of yielding anthocyanins, flavanones, flavanols, and condensed tannins, or proanthocyanidins. The p-coumaric acid, caffeic acid, cinnamic acid, ferulic acid, gallic acid, salicylic acid and vanillic acid make up a significant portion of the phenolic acids present in sorghum (50). The principal flavonoids found in sorghum are luteolin, apigenin, eriodictyol and naringenin (51) (Table 6).

Anthocyanin content

The need for natural food colorants with nutraceutical

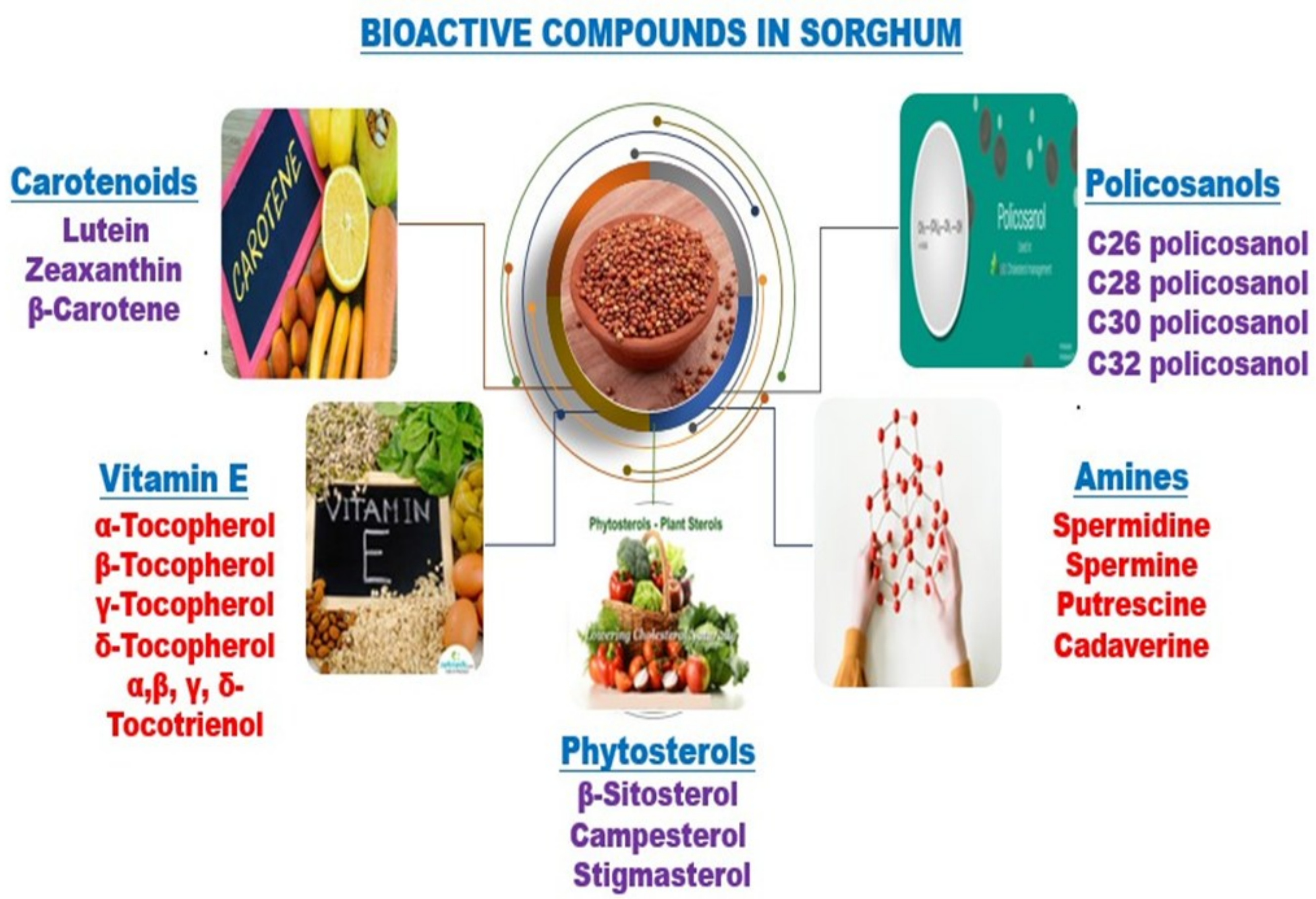

Fig. 4. Bioactive compounds in sorghum.

Table 5. Concentration of bioactive components in sorghum grains (89)

Bioactive Components	Content	Unit	Reference
Carotenoids			
Lutein (red and white cultivar)	24.6, 122.3	mg/kg	
Zeaxanthin (red and white cultivar)	25.3, 73	mg/kg	(90)
β-Carotene (red and white cultivar)	27, 34.3	mg/kg	
Vitamin E			
α-Tocopherol	1.22–5.26	µg/g	(91)
β-Tocopherol	0–784.7	µg/100g	
γ-Tocopherol	174.6–2109	µg/100g	
δ-Tocopherol	0–379.8	µg/100g	
α-Tocotrienol	0–311.9	µg/100g	(92)
β-Tocotrienol	0–850.5	µg/100g	
γ-Tocotrienol	0–270.5	µg/100g	
δ-Tocotrienol	0–484.2	µg/100g	
Amines			
Spermidine	0.5–18.7	mg/kg	
Spermine	2.7–27.2	mg/kg	(93)
Putrescine	0.7–7.2	mg/kg	
Cadaverine	0–0.6	mg/kg	
Policosanols and phytosterols			
β-Sitosterol	17.75–32.32	mg/kg	(94)
Campesterol	1.04	mg/g of lipids	
Stigmasterol	1.02	mg/g of lipids	
C26 policosanol	1.53	mg/g of lipids	
C28 policosanol	2.7	mg/g of lipids	(95)
C30 policosanol	1.31	mg/g of lipids	
C32 policosanol	0.25	mg/g of lipids	

properties is growing, and other forms of naturally occurring anthocyanins are playing a bigger role. Anthocyanins, which serve as antioxidants and food colorants, are gaining increasing significance. They have been associated with numerous therapeutic benefits, including anti-neoplastic, anti-cancer, and chemoprotective effects, as well as vasoprotective and anti-inflammatory properties. A considerable quantity of anthocyanins along with various phenols is contained in the bran of specialty sorghum varieties (52). Anthocyanin pigments in black sorghum were found to be substantially higher than other kinds of sorghums (52). Sorghum's anthocyanins, primarily 3-deoxyanthocyanidins, are more heat- and acid-resistant than berry anthocyanins like cyanidin and delphinidin. This makes them better suited for food processing, though berry anthocyanins are more powerful antioxidants but break down faster. Sorghum anthocyanins have lower bioavailability but may positively impact gut health, while berry anthocyanins act quickly, providing short-term antioxidant benefits. Both types serve distinct roles, with sorghum thriving in functional foods and berries favored for their vibrant colors and health-enhancing properties. Using paper chromatography, Nip and Burns (1969, 1971) were separated and identified luteolinidin, luteodin-5-glucoside, apigeninidin and luteolinidin in sorghum cultivars. Apigeninidin and luteolinidin as the main anthocyanidins derived from a species of black sorghum. Additionally, maize (53) and the sorghum (54) have been reported to contain pelargonidin and cyanidin. The 3-deoxyanthocyanidins (luteolinidin and apigeninidin) are the most prevalent anthocyanins found in sorghum. The C-3 position of these anthocyanins is devoid of oxygen, which sets them apart from the more extensively dispersed anthocyanidins. This is why these anthocyanins are rare in nature (55). Sorghum may have an advantage over vegetable and fruit products in terms of stability and viability as an industrial source of anthocyanins due to the absence of oxygen at carbon-3. Interestingly the study which examined the growth inhibitory effects of sorghum-derived anthocyanins on MCF-7 cells, observed significant morphological changes even at a concentration of 1000 µg/mL. These anthocyanins effectively suppressed the proliferation of human breast tumor cell lines. The study also documented the anticancer properties of various flavonoids against human breast cancer using the MCF-7 cell line (56). By employing the MCF-7 cell line, the anticancer properties of flavonoids, such as flavanones, daidzein, genistein, quercetin and luteolin in human breast cancer (57).

Therapeutic properties in sorghum

Sorghum enhances food quality, nutrition, and health by being incorporated as both an ingredient and a standalone product, thereby yielding functional foods. Sorghum may be used as a potential healthful component in pasta, a well -known universal staple dish made with semolina from durum wheat (58). For instance, the complex carbohydrates, phenolic compounds, and antioxidant qualities of pasta are greatly increased when 20% to 40% of the semolina is substituted with sorghum whole grain flour. On the other hand, it has been demonstrated that sorghum meal in high amounts diminishes sensory qualities and consumer approval. If 20–30% of the flour contains sorghum, it is possible to produce pasta with a similar texture while maintaining nutritional value and health benefits (59). Eating red sorghum (rich in phenolic compounds) linguine, in addition to light sorghum, enhanced people's health by increasing plasma phenolic concentration and antioxidant capacity. It has also been shown that muffins made with sorghum contain a substantial amount of complex and hard-to-digest carbohydrates (46). To increase sorghum's health advantages, it may also be used in Chinese steamed bread (60). The full-grain sorghum flour, either red or white, performs well as a wheat flour substitute in bread, significantly enhancing its phenolic and antioxidant characteristics (61) (Fig. 5). Although sorghum is one of the most commonly used kernels in animal feed, it is not used

Table 6. List of sorghum phenolic compounds in sorghum

Phenolic Compounds	Content (ug/g)	Nutraceutical properties	References
Hydrocinnamic acids			
Caffeic acid	13.55–20.80	Antioxidant, antitumor, anti-inflammatory, antimicrobial and antidiabetic activity	(89)
p-Coumaric acid	41.88–71.88	Antioxidant, antimicrobial, antitumor, anti-inflammatory, antiplatelet aggregation	(89)
Ferulic acid	120.47–163.91	Antioxidant, antitumor, anti-inflammatory, antimicrobial and antidiabetic activity	(89)
Sinapic acid	8.22	Anti-inflammatory	(96)
Chlorogenic acid	235.91–293.19	Anti-inflammatory	(97)
Cinnamic acid	9.76–15.02	Anti-inflammatory	(89)
Hydrobenzoic acids			
Protocatechuic acid	150.28–178.22	Antioxidant	(89)
p-Hydroxybenzoic acid	6.13–16.39	Antioxidant, antitumor, anti-inflammatory	(89)
3,4-Dihydroxybenzoic acid	Soluble 0–369.52; Bound 33–454.54	Antitumor, anti-inflammatory	(98)
Vanillic acid	15.45–23.43	Anticancer activity	(97)
Salicylic acid	63.4	Anti-inflammatory	(96)
Gallic acid	14.84–21.51	Anticancer activity	(89)
Syringic acid	15.71–17.48	Anti-inflammatory	(89)
Flavonoids (3-Deoxyanthocyanidin)			
Luteolinidin	Soluble 20.39–57.14; Bound 0.06–0.15	Antioxidant	(98)
Apigeninidin	Soluble 4.76–13.04; Bound 0.01–0.04	Antioxidant	(98)
5-Methoxyluteolinidin	Soluble 2.23–6.04; Bound 0.-0.04	Anti-inflammatory	(98)
7-Methoxyapigeninidin	Soluble 5.25–16.82; Bound 0.01–0.05	Anti-inflammatory	(98)
5-Methoxyluteolinidin 7-glucoside	0.18	Antiobesity	(97)
Luteolinidin 5-glucoside	0.11	Antiobesity	(97)
7-Methoxyapigeninidin 5-glucoside	0.23	Antiobesity	(97)
Apigeninidin 5-glucoside	0.07	Antiobesity	(97)
Luteolinidin anthocyanin	0.09	Antiobesity	(97)
Flavones			
Luteolin	112.56–210.70	Antioxidant	(89)
Apigenin	25.74–65.58	Antibacterial	(89)
Vitexin	0.50	Antibacterial	(90)
Flavanones			
Naringenin	22.85–28.62	Antioxidant, antibacterial activity	(89)
Naringenin hexoside	13,330	Antioxidant, antibacterial activity	(99)
Flavonols			
Kaempferol	17.88–36.44	Anticancer activity	(89)
Quercetin	22.34–29.43	Antineoplastic activity, Anticancer activity, anti-proliferative agent	(89)
Quercetin diglucoside	8420	Anticancer activity	(99)
Rutin	10,290	Anticancer activity	(99)
Flavanols			
Catechin	5.58–6.13	Antimicrobial activity	(89)
Epicatechin	112,860	Anti-inflammatory	(99)
Dihydroflavonol			
Taxifolin	27,020	Anti-inflammatory	(99)
Taxifolin hexoside I	25,470	Anti-inflammatory	(99)
Taxifolin hexoside II	3680	Anti-inflammatory	(99)
Tannins			
Dimer procyanidin	178,860	Anti-inflammatory	(99)
Trimer procyanidin	51,380	Anti-inflammatory	(99)
Tetramer procyanidin	167,550	Anti-inflammatory	(99)

very effectively. Certain sorghums, particularly those high in tannins, may exhibit antinutritional properties that obstruct increased feed production (62).

Anti-oxidant activity

Phenolic compounds in sorghum play a crucial role in disease prevention and health promotion due to their superior antioxidant activity compared to other cereal grains. Strong correlations have been shown between the total phenolic content and antioxidant activity, particularly with condensed tannins (63). Sorghum has higher antioxidant potential than most grains due to its rich content of polyphenols and unique 3-deoxyanthocyanidins, especially in pigmented varieties like red and black sorghum. While grains like wheat and barley contain antioxidants, they generally have lower levels of bioactive compounds compared to sorghum. Maize and black rice can match or exceed sorghum's antioxidant activity, but this is typically limited to their pigmented varieties. Condensed tannins in sorghum, especially in the bran, which is rich in phenolic compounds, exhibit significant antioxidant activity, potentially improving human health by mitigating inflammation in ailments, such as cardiovascular illnesses and preventing chronic disorders related to nitric oxide (NO) synthetase and xanthine oxidase (64). Furthermore, adding sorghum to Chinese steamed bread significantly increased the bread's cellular antioxidant activity (61). Additionally, phenolic extracts from black and brown sorghum bran exhibited the highest antioxidant activity. Compared to NO radicals, sorghum extracts demonstrated higher DPPH scavenging action (65).

Anti-obesity

An abundance of whole-grain sorghum in the diet can benefit individuals with diabetes and obesity due to its low digestibility. Kafirin, a protein present in sorghum, forms robust disulfide bonds with starch, creating a cross-links that resist digestion (66). Additionally, sorghum tannins react with proteins and carbohydrates in the gastrointestinal system, leading to the formation of less digestible and non-digestible bulk complexes (12). Compared to phenolics, sorghum tannins interact with starch in a far more complex manner and the stronger the interaction, the larger the molecular weight of the tannin (67). Obese and diabetic individuals benefit from the combination's ability to promote satiety, lower calorie intake and induce a low glycemic response (68). When eating whole-grain sorghum biscuits, healthy individuals rated their levels of hunger and satiety higher than when eating wheat biscuits (69).

Antidiabetic

Sorghum stands out as a potential antidiabetic due to its rich content of antioxidants and phytochemicals, particularly polyphenols. Among major cereals, sorghum's abundance of these compounds, known for their preventive properties against metabolic syndromes, such as type 2 diabetes, obesity, hypertension and certain

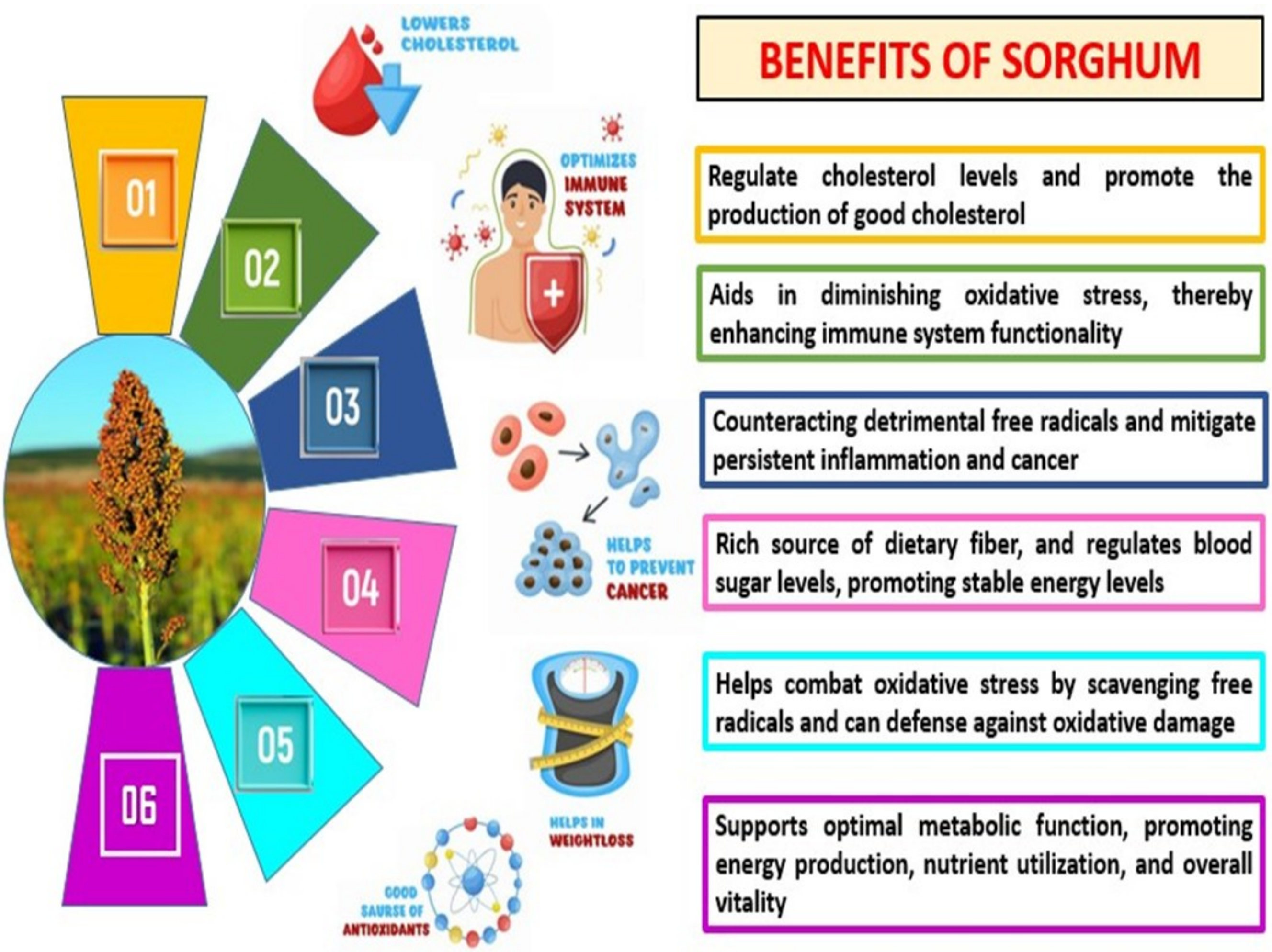

Fig. 5. Therapeutic properties in sorghum.

cancers, makes it noteworthy (70). Phenolics from sorghum can regulate insulin and may serve as an additive in the treatment of diabetes (71). Studies have shown that sorghum-based foods, like muffins, can improve glycemic responses and influence insulin and blood glucose levels in healthy individuals (60). The antidiabetic properties of condensed tannins are one of the reasons for the use of sorghum. The unprocessed extract from tannin sorghum type III exhibits a significant inhibitory action against yeast α-glucosidase, about 20,000 times more than acarbose (72). An earlier study using diabetic rats treated with streptozotocin (STZ) showed that sorghum extract reversed increases in blood sugar and triacylglycerol, which were linked to the activation of AMP-activated protein kinase (AMPK) and a reduction in macrophage infiltration in the liver (73). Adding proanthocyanidins and deoxyanthocyanins to sorghum drinks significantly reduces excess glycemia compared to non-sorghumbased drinks (74). Therefore, the active starch, proanthocyanidins, and deoxyanthocyanins found in whole-grain sorghum appear to be beneficial functional dietary components that enhance glucose metabolism (75).

Anti-cancer properties

Globally, cancer is the leading cause of mortality and sorghum's bioactive compounds, including flavonoids and phenolic acids, possess anti-cancer properties that target multiple cancer symptoms. Flavones found in sorghum exhibit estrogenic characteristics and have demonstrated anticancer effects *in vitro* (76). Redox signals induce oxidative stress in cancer cells, deactivating tumour suppressor genes (p53) and activating signalling proteins (NF-kB and AP-1), thereby fostering cancer growth. Maintaining an antioxidant-rich diet is crucial for preventing illnesses caused by oxidative stress. Apoptosis safeguards tissues by preventing inflammation and mutations in neighbouring cells, ensuring their survival. Its disruption can lead to unchecked tumour cell proliferation and malignancies (77). Sorghum tannins have potential in cancer prevention by blocking aromatase, an enzyme linked to breast cancer (78). Brown sorghum bran extract, rich in tannins, is more effective than 3-deoxyanthocyanidin-rich extracts at reducing aromatase activity (78). Sorghum-derived tannins outperform grape seed tannins in inhibiting the growth of colon cancer cells (79, 80).

Anti-inflammatory function

Chronic inflammation, often caused by prolonged oxidative stress, can lead to various chronic illnesses. Inflammation triggers the production of chemicals such as prostaglandin E2 (PG-E2), interleukin (IL), cyclooxygenase (COX)-2 and tumour necrosis factor (TNF). However, phenolic compounds found in sorghum grains have been shown to inhibit the formation of these inflammatory substances (81). For instance, it has been demonstrated that phenolic acids like ferulic acid and gallic acid suppress the COX2 enzyme, and that ferulic acid reduces the production of prostaglandin E2 (PG-E2) and (TNF)-α. The flavones luteolin and apigenin inhibit the synthesis of COX-2 and nuclear factor kappa B (NF-κB), the transcription factor that regulates the synthesis of inflammatory compounds (82). 3-Deoxyanthocyanidins inhibited the production of PG-E2 and COX-2 (81). By arranging the conjugation C2 = C3, apigenin and quercetin can significantly enhance the anti-inflammatory activity (83). Similar to the anti-inflammatory drug indomethacin, the crude phenolic extract from sorghum bran, especially black, has also demonstrated a potent inhibitory impact on the proinflammatory activity of COX-2, IL-1β, and TNF-α. Recent studies have shown that adding full-grain sorghum biscuits to the diet of overweight individuals can significantly reduce pro-inflammatory chemicals such as IL -1β, IL-6, IL-8 and TNF α over a 12-week period (69). Additionally, the hyaluronidase enzyme, which is implicated in chronic joint inflammation, was suppressed by the phenol extraction from sorghum bran. Regardless of the pericarp colors and condensed tannin level, all sorghum genotypes exhibited considerable inhibition against hyaluronidase activity. In addition to phenols, sorghum's triacylglycerols, tocopherols, carotenoids and unsaturated fatty acids have been proven to possess anti-inflammatory properties via lowering the expression of certain genes in lipopolysaccharides (LPS) (68).

Antidiarrheal properties

Diarrhoea, characterized by loose stools, increased bowel movements, and stomach discomfort, poses a significant global health threat, particularly in underdeveloped regions lacking access to proper sanitation and clean water. Research is ongoing in response to the World Health Organization's recognition of the urgent need for effective treatments and preventive measures for diarrheal diseases. Sorghum, a vital food crop in Asia, Europe, and Africa, is being investigated for its potential in treating a range of illnesses, including diarrhoea, malaria, stomach-aches (84). A study in Africa explored the use of sorghum in treating malnutrition-related diarrhea in children. Sorghum-based meals, owing to their nutrient density and astringent properties, were shown to help reduce the severity and duration of diarrhea in malnourished children. Additionally, the antibacterial action against *Staphylococcus aureus* and *Escherichia coli* has also been reported. Some scientific study suggest that sorghum may be used as an antidiarrheal medication.

Conclusion

The review highlights the immense potential of sorghum in nutrition, health, and food security. Its robust nutritional profile, including high fiber and protein content along with essential minerals, positions it as a valuable food source. With attributes such as resistant starch, fiber, bioactive substances, kafirin protein, and being naturally gluten-free, sorghum offers advantages for diabetes management and possesses antioxidant properties. Its drought-resistant and versatile nature makes it a promising solution to address nutritional needs, particularly in climate-vulnerable regions. Various sorghum-derived products, ranging from flour to beverages, cater to evolving dietary preferences and health-conscious diets. Sorghum's functional composition, including tannins known for combating against inflammation and cancer, and its high fiber content which benefits individuals with celiac disease, contribute positively to human health by reducing the risk of chronic diseases such as diabetes and cardiovascular diseases. There is a growing need for researchers and policymakers to prioritize the development of sorghum as a key crop to address the dual challenges of food security and climate resilience, particularly in climate-affected regions. By enhancing breeding programs to improve yield and nutrient content and by implementing supportive policies for sorghum cultivation, stakeholders can promote sustainable agriculture and dietary diversity. Investing in sorghum can ensure more resilient food systems in vulnerable regions while advancing global efforts in climate adaptation. Future opportunities lie in improving sorghum quality through genomics and advanced food processing methods, potentially exploring its use as a biofortified crop to enhance nutritional security. As sorghum emerges as a leader in environmentally friendly agriculture and nutrition, sustained attention and funding from agro-industries, academics, and policymakers will be crucial. In conclusion, sorghum millet stands out as an exceptional option for a nutrient-dense food crop.

Acknowledgements

The authors sincerely acknowledge to the Tamil Nadu Agricultural University (TNAU) for providing the necessary resources, facilities, and support for writing this review. We acknowledge the valuable guidance and encouragement from faculty members and colleagues, who greatly contributed to the completion of this review article.

Authors' Contributions

Conceptualization and writing were carried out by SJ, with review and editing contributions from RC, SS, KC, VVAG and NMB. All the authors have read and agreed to the published version of the manuscript.

Compliance with Ethical Standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

1. Soni J, Sheikh FS, Saha S, Wanjari MB, Saxena D. Nutritional indicators for Gujarat, its determinants and recommendations: A comparative study of national family health survey-4 and national family health survey-5. Cureus. 2023;15:5. https://doi.org/10.7759%2Fcureus.39175
2. World Health Organization. Fact sheets-malnutrition. World Health Organization [Internet]. 2021. https://www.who.int/news-room/factsheets/detail/malnutrition
3. World Health Organization. The State of Food Security and Nutrition in the World 2023: Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum. Food and Agriculture Org.; 2023. https://doi.org/10.4060/cc3017en
4. Anglani C. Sorghum for human food–A review. Plant Foods Human Nutri. 1998;52:85–95. https://doi.org/10.1023/A:1008065519820
5. FAO Stat. Available online: http://www.fao.org/faostat/en/#data. QC. 2017.
6. Awika JM, Rooney LW. Sorghum phytochemicals and their potential impact on human health. Phytochem. 2004;65(9):1199221. https://doi.org/10.1016/j.phytochem.2004.04.001
7. Lee SH, Lee J, Herald T, Cox S, Noronha L, Perumal R, et al. Anticancer activity of a novel high phenolic sorghum bran in human colon cancer cells. Oxidative Med Cellular Longev. 2020;2020(1):2890536. https://doi.org/10.1155/2020/2890536
8. Miafo AP, Koubala BB, Kansci G, Muralikrishna G. Antioxidant properties of free and bound phenolic acids from bran, spent grain and sorghum seeds. Cereal Chem. 2020;97(6):1236–43. https://doi.org/10.1002/cche.10348
9. Shen S, Huang R, Li C, Wu W, Chen H, Shi J, et al. Phenolic compositions and antioxidant activities differ significantly among sorghum grains with different applications. Molecules. 2018;23(5):1203. https://doi.org/10.3390/molecules23051203
10. Ghonaim MM, Mohamed HI, Omran AA. Evaluation of wheat (*Triticum aestivum* L.) salt stress tolerance using physiological parameters and retrotransposon-based markers. Genet Resour Crop Evol. 2021;68(1):227–42. https://doi.org/10.1007/s10722-020-00981-w
11. Mohamed HI, Ashry NA, Ghonaim MM. Physiological and biochemical effects of heat shock stress and determination of molecular markers related to heat tolerance in maize hybrids. Gesunde Pflanzen. 2019;71(3):213. https://doi.org/10.1007/s10722-020-00981-w
12. Lee SH, Lee HS, Lee J, Amarakoon D, Lou Z, Noronha LE, et al. Polyphenol containing sorghum brans exhibit an anti-cancer effect in Apc Min/+ mice treated with dextran sodium sulfate. Int J Mol Sci. 2021;22(15):8286. https://doi.org/10.3390/ijms22158286
13. Li S, Cheng CS, Zhang C, Tang GY, Tan HY, Chen HY, et al. Edible and herbal plants for the prevention and management of COVID-19. Front Pharmac. 2021;12:656103. https://doi.org/10.3389/fphar.2021.656103
14. Swaminathan S, Dehghan M, Raj JM, Thomas T, Rangarajan S, Jenkins D, et al. Associations of cereal grains intake with cardiovascular disease and mortality across 21 countries in prospective urban and rural epidemiology study: Prospective cohort study. Bmj. 2021;372. https://doi.org/10.1136/bmj.m4948
15. Verma DK, Srivastav PP. Bioactive compounds of rice (*Oryza sativa* L.): Review on paradigm and its potential benefit in human health. Trends Food Sci Tech. 2020;97:355–65. https://doi.org/10.1016/j.tifs.2020.01.007
16. Earp CF, McDonough CM, Awika J, Rooney LW. Testa development in the caryopsis of *Sorghum bicolor* (L.) Moench. J Cereal Sci. 2004;39(2):303–11. https://doi.org/10.1016/j.jcs.2003.11.005
17. Chandrashekar A, Kirleis AW. Influence of protein on starch gelatinization in sorghum. Cereal Chem. 1988;65(6):457–62. http://ir.cftri.res.in/id/eprint/4440

18. Adams CA, Novellie L, Liebenberg NV. Biochemical properties and ultrastructure of protein bodies isolated from selected cereals. Cereal Chem. 1976;53(1):1–12.

19. Chandrashekar A, Desikachar HS. Sorghum quality studies. II. Suitability for making dumpling (mudde). J Food Sci Tech. 1986;23(1):7–10. http://ir.cftri.res.in/id/eprint/6456

20. Rooney LW. Sorghum and pearl millet lipids. Cereal Chem. 1978;55(5):584–90.

21. Udachan IS, Sahoo AK, Hend GM. Extraction and characterization of sorghum (*Sorghum bicolor* L. Moench) starch. Int Food Res J. 2012;19(1):315.

22. Dicko MH, Gruppen H, Zouzouho OC, Traoré AS, Van Berkel WJ, Voragen AG. Effects of germination on the activities of amylases and phenolic enzymes in sorghum varieties grouped according to food end-use properties. J Sci Food Agric. 2006;86(6):953–63. https://doi.org/10.1002/jsfa.2443

23. Barros F, Awika J, Rooney LW. Effect of molecular weight profile of sorghum proanthocyanidins on resistant starch formation. J Sci Food Agric. 2014;94(6):1212–17. https://doi.org/10.1002/jsfa.6400

24. Martino HS, Tomaz PA, Moraes EA, Conceição LD, Oliveira DD, Queiroz VA, et al. Chemical characterization and size distribution of sorghum genotypes for human consumption. Rev Inst Adolfo Lutz. 2012;71(2):337-44. https://doi.org/10.53393/rial.2012.v71.32433

25. Verbruggen MA, Spronk BA, Schols HA, Beldman G, Voragen AG, Thomas JR, et al. Structures of enzymically derived oligosaccharides from sorghum glucuronoarabinoxylan. Carbohydr Res. 1998;306(1-2):265-274. https://doi.org/10.1016/S0008-6215(97)10064-7

26. Li H, Li Z, Peng P, She D, Xu Q, Zhang X. Characteristics of hemicelluloses obtained from sweet sorghum based on successive extractions. J Appl Polymer Sci. 2015;132(46). https://doi.org/10.1002/app.42790

27. Mishra A, Malhotra AV. Tamarind xyloglucan: A polysaccharide with versatile application potential. J Mater Chem. 2009;19(45):8528–36. https://doi.org/10.1039/B911150F

28. Belton PS, Delgadillo I, Halford NG, Shewry PR. Kafirin structure and functionality. J Cereal Sci. 2006;44(3):272–86. https://doi.org/10.1016/j.jcs.2006.05.004

29. Hoseney RC, Faubion JM. A mechanism for the oxidative gelation of wheat flour water-soluble pentosans. Cereal Chem. 1981;58(5):421–24.

30. Wrigley CW, Corke H, Walker CE. Encyclopedia of grain science. Vol. 2. Academic Press.; 2004. p. 500.

31. Jiang SY, Ma A, Xie L, Ramachandran S. Improving protein content and quality by over-expressing artificially synthetic fusion proteins with high lysine and threonine constituent in rice plants. Sci Rep. 2016;6(1):34427. https://doi.org/10.1038/srep34427

32. Khan A, Khan NA, Bean SR, Chen J, Xin Z, Jiao Y. Variations in total protein and amino acids in the sequenced sorghum mutant library. Plants. 2023;12(8):1662. https://doi.org/10.3390/plants12081662

33. Pedersen B, Eggum BO. The influence of milling on the nutritive value of flour from cereal grains. 6. Sorghum. Plant Foods for Human Nutri. 1983;33:313–26. https://doi.org/10.1007/BF01094756

34. Mbofung CM, Ndjouenkeu R. Influence of milling method and peanut extract on *in vitro* iron availability from maize and sorghum flour gruels. J Food Sci. 1990;55(6):1657–59. https://doi.org/10.1111/j.1365-2621.1990.tb03593.x

35. Gillooly M, Bothwell TH, Charlton RW, Torrance JD, Bezwoda WR, MacPhail AP, et al. Factors affecting the absorption of iron from cereals. Br J Nutri. 1984;51(1):37-46. https://doi.org/10.1079/BJN19840007

36. Radhakrishnan MR, Sivaprasad J. Tannin content of sorghum varieties and their role in iron bioavailability. J Agric Food Chem. 1980;28(1):55–57. https://doi.org/10.1021/jf60227a038

37. Elhassan MS, Emmambux MN, Hays DB, Peterson GC, Taylor JR. Novel biofortified sorghum lines with combined waxy (high amylopectin) starch and high protein digestibility traits: Effects on endosperm and flour properties. J Cereal Sci. 2015;65:132–39. https://doi.org/10.1016/j.jcs.2015.06.017

38. Ferreira SM, de Mello AP, dos Anjos MD, Krüger CC, Azoubel PM, de Oliveira Alves MA. Utilization of sorghum, rice, corn flours with potato starch for the preparation of gluten-free pasta. Food Chem. 2016;191:147–51. https://doi.org/10.1016/j.foodchem.2015.04.085

39. Afandi FA, Wijaya CH, Faridah DN, Suyatma NE, Jayanegara A. Evaluation of various starchy foods: A systematic review and meta-analysis on chemical properties affecting the glycemic index values based on *in vitro* and *in vivo* experiments. Foods. 2021;10(2):364. https://doi.org/10.3390/foods10020364

40. Dykes L, Rooney WL, Rooney LW. Evaluation of phenolics and antioxidant activity of black sorghum hybrids. J Cereal Sci. 2013;58(2):278–83. https://doi.org/10.1016/j.jcs.2013.06.006

41. Awika JM, Yang L, Browning JD, Faraj A. Comparative antioxidant, antiproliferative and phase II enzyme inducing potential of sorghum (*Sorghum bicolor*) varieties. LWT-Food Sci and Techno. 2009;42(6):1041–46. https://doi.org/10.1016/j.lwt.2009.02.003

42. Awika JM, Rooney LW, Waniska RD. Anthocyanins from black sorghum and their antioxidant properties. Food Chem. 2005;90(1-2):293–301. https://doi.org/10.1016/j.foodchem.2004.03.058

43. Shim TJ, Kim TM, Jang KC, Ko JY, Kim DJ. Toxicological evaluation and anti-inflammatory activity of a golden gelatinous sorghum bran extract. Biosci Biotech Biochem. 2013;77(4):697–705. https://doi.org/10.1271/bbb.120731

44. Kayodé AP, Hounhouigan DJ, Nout MJ, Niehof A. Household production of sorghum beer in Benin: Technological and socio-economic aspects. Int J Consumer Std. 2007;31(3):258–64. https://doi.org/10.1111/j.1470-6431.2006.00546.x

45. Xiong Y, Zhang P, Warner RD, Fang Z. Sorghum grain: From genotype, nutrition and phenolic profile to its health benefits and food applications. Comp Rev Food Sci Food Safety. 2019;18(6):2025–46. https://doi.org/10.1111/1541-4337.12506

46. Khan I, Yousif AM, Johnson SK, Gamlath S. Acute effect of sorghum flour-containing pasta on plasma total polyphenols, antioxidant capacity and oxidative stress markers in healthy subjects: A randomised controlled trial. Clin Nutri. 2015;34(3):415–21. https://doi.org/10.1016/j.clnu.2014.08.005

47. Wierzbicka D, Gromadzka G. Ceruloplasmin, hephaestin and zyklopen: The three multicopper oxidases important for human iron metabolism. Adv Hyg Exp Med. 2014;68:912–24. https://doi.org/10.5604/17322693.1111136

48. Helman SL, Zhou J, Fuqua BK, Lu Y, Collins JF. The biology of mammalian multi-copper ferroxidases. Biometals. 2023;36(2):263–81. https://doi.org/10.1007/s10534-022-00370-z

49. Sharma P, Reichert M, Lu Y, Markello TC, Adams DR, Steinbach PJ, et al. Biallelic HEPHL1 variants impair ferroxidase activity and cause an abnormal hair phenotype. PLoS Genet. 2019;15(5):e1008143. https://doi.org/10.1371/journal.pgen.1008143

50. Li R, Wang Q, Zhao G, Peng H, Zhang D, Li Z. Effects of germination time on phenolics, antioxidant capacity, *in vitro* phenolic bioaccessibility and starch digestibility in sorghum. Int J Food Sci Tech. 2022;57(8):5175–85. https://doi.org/10.1111/ijfs.15827

51. Apea-Bah FB, Li X, Beta T. Phenolic composition and antioxidant properties of cooked rice dyed with sorghum-leaf bio-colorants. Foods. 2021;10(9):2058. https://doi.org/10.3390/foods10092058

52. Awika JM. Sorghum phenols as antioxidants. Doctoral [Thesis], Texas A and M University; 2000. https://hdl.handle.net/1969.1/ETD-TAMU-2000-THESIS-A96

53. Francis FJ, Markakis PC. Food colorants: Anthocyanins. Crit Rev Food Sci Nutri. 1989;28(4):273–314. https://doi.org/10.1080/10408398909527503

54. Yasumatsu K, Nakayama TO, Chichester CO. Flavonoids of sorghum. J Food Sci. 1965;30(4):663–67. https://doi.org/10.1111/j.1365-2621.1965.tb01821.x

55. Clifford MN. Anthocyanins–nature, occurrence and dietary burden. J Sci Food Agric. 2000;80(7):1063–72. https://doi.org/10.1002/(SICI)1097-0010(20000515)80:7%3C1063::AID-JSFA605%3E3.0.CO;2-Q

56. Devi PS, Kumar MS, Das SM. Evaluation of antiproliferative activity of red sorghum bran anthocyanin on a human breast cancer cell line (MCF-7). Int J Breast Cancer. 2011;2011(1):891481. https://doi.org/10.4061/2011/891481

57. Pouget C, Lauthier F, Simon A, Fagnere C, Basly JP, Delage C, et al. Flavonoids: Structural requirements for antiproliferative activity on breast cancer cells. Bioorg Med Chem Lett. 2001;11(24):3095–97. https://doi.org/10.1016/S0960-894X(01)00617-5

58. Khan I, Yousif A, Johnson SK, Gamlath S. Effect of sorghum flour addition on resistant starch content, phenolic profile and antioxidant capacity of durum wheat pasta. Food Res Int. 2013;54(1):578–86. https://doi.org/10.1016/j.foodres.2013.07.059

59. Khan I, Yousif AM, Johnson SK, Gamlath S. Effect of sorghum flour addition on *in vitro* starch digestibility, cooking quality and consumer acceptability of durum wheat pasta. J Food Sci. 2014;79(8):S1560–67. https://doi.org/10.1111/1750-3841.12542

60. Poquette NM, Gu X, Lee SO. Grain sorghum muffin reduces glucose and insulin responses in men. Food and Funct. 2014;5(5):894–99. https://doi.org/10.1039/C3FO60432B

61. Wu G, Shen Y, Qi Y, Zhang H, Wang LI, Qian H, et al. Improvement of *in vitro* and cellular antioxidant properties of Chinese steamed bread through sorghum addition. Lwt. 2018;91:77-83. https://doi.org/10.1016/j.lwt.2017.12.074

62. Di Donfrancesco B, Koppel K, Aldrich CG. Pet and owner acceptance of dry dog foods manufactured with sorghum and sorghum fractions. J Cereal Sci. 2018;83:42–48. https://doi.org/10.1016/j.jcs.2018.07.011

63. Moustafa-Farag M, Mohamed HI, Mahmoud A, Elkelish A, Misra AN, Guy KM, et al. Salicylic acid stimulates antioxidant defense and osmolyte metabolism to alleviate oxidative stress in watermelons under excess boron. Plants. 2020;9(6):724. https://doi.org/10.3390/plants9060724

64. Nagy R, Szőllősi E, Molnár PB, Murányi E, Czimbalmos R, Sipos P. Condensed tannin content and antioxidant activity of Hungarian sorghum varieties grown at Research Institute in Karcag. Acta Agraria Debreceniensis. 2021;1(1):155–60. https://doi.org/10.34101/actaagrar/1/8467

65. Hong S, Pangloli P, Perumal R, Cox S, Noronha LE, Dia VP, et al. A comparative study on phenolic content, antioxidant activity and anti-inflammatory capacity of aqueous and ethanolic extracts of sorghum in lipopolysaccharide-induced RAW 264.7 macrophages. Antioxidants. 2020;9(12):1297. https://doi.org/10.3390/antiox9121297

66. Ezeogu LI, Duodu KG, Emmambux MN, Taylor JR. Influence of cooking conditions on the protein matrix of sorghum and maize endosperm flours. Cereal Chem. 2008;85(3):397–402. https://doi.org/10.1094/CCHEM-85-3-0397

67. Barros F, Awika JM, Rooney LW. Interaction of tannins and other sorghum phenolic compounds with starch and effects on *in vitro* starch digestibility. J Agric Food Chem. 2012;60(46):11609–17. https://doi.org/10.1021/jf3034539

68. Mohamed HI, Elsherbiny EA, Abdelhamid MT. Das physiologische und biochemische Ansprechen von *Vicia faba* auf die Blattbehandlung mit Zink und Eisen. Gesunde Pflanzen. 2016;68:201–12. https://doi.org/10.1007/s10343-016-0378-0

69. Stefoska-Needham A, Beck EJ, Johnson SK, Chu J, Tapsell LC. Flaked sorghum biscuits increase postprandial GLP-1 and GIP levels and extend subjective satiety in healthy subjects. Mol Nutri Food Res. 2016;60(5):1118–28. https://doi.org/10.1002/mnfr.201500672

70. Awika JM, Rose DJ, Simsek S. Complementary effects of cereal and pulse polyphenols and dietary fiber on chronic inflammation and gut health. Food Funct. 2018;9(3):1389–409. https://doi.org/10.1039/C7FO02011B

71. Kim J, Park Y. Anti-diabetic effect of sorghum extract on hepatic gluconeogenesis of streptozotocin-induced diabetic rats. Nutri Metabol. 2012;9:1–7. https://doi.org/10.1186/1743-7075-9-106

72. Links MR, Taylor J, Kruger MC, Taylor JR. Sorghum condensed tannins encapsulated in kafirin microparticles as a nutraceutical for inhibition of amylases during digestion to attenuate hyperglycaemia. J Funct Foods. 2015;12:55–63. https://doi.org/10.1016/j.jff.2014.11.003

73. Mukai Y, Kataoka S, Sato S. Sorghum (*Sorghum bicolor*) extract affects plasma lipid metabolism and hepatic macrophage infiltration in diabetic rats. Current Nutri Food Sci. 2020;16(5):824–32. https://doi.org/10.2174/1573401315666190114153933

74. Anunciação PC, Cardoso LD, Queiroz VA, de Menezes CB, de Carvalho CW, Pinheiro-Sant'Ana HM, et al. Consumption of a drink containing extruded sorghum reduces glycaemic response of the subsequent meal. Europ J Nutri. 2018;57:251-57. https://doi.org/10.1007/s00394-016-1314-x

75. Amarakoon D, Lou Z, Lee WJ, Smolensky D, Lee SH. A mechanistic review: Potential chronic disease-preventive properties of sorghum. J Sci Food Agric. 2021;101(7):2641–49. https://doi.org/10.1002/jsfa.10933

76. Cox S, Noronha L, Herald T, Bean S, Lee SH, Perumal R, et al. Evaluation of ethanol-based extraction conditions of sorghum bran bioactive compounds with downstream anti-proliferative properties in human cancer cells. Heliyon. 2019;5(5):e01589. https://doi.org/10.1016/j.heliyon.2019.e01589

77. Ryu JM, Jang GY, Woo KS, Kim TM, Jeong HS, Kim DJ. Effects of sorghum ethyl-acetate extract on PC3M prostate cancer cell tumorigenicity. J Funct Foods. 2017;37:449–59. https://doi.org/10.1016/j.jff.2017.07.063

78. Hargrove JL, Greenspan P, Hartle DK, Dowd C. Inhibition of aromatase and α-amylase by flavonoids and proanthocyanidins from *Sorghum bicolor* bran extracts. J Med Food. 2011;14(7-8):799–807. https://doi.org/10.1089/jmf.2010.0143

79. Awika JM. Sorghum flavonoids: Unusual compounds with promising implications for health. In: Advances in cereal science: Implications to food processing and health promotion; 2011. 9:171-200. https://doi.org/10.1021/bk-2011-1089.ch009

80. Lee S, Choi YM, Shin MJ, Yoon H, Wang X, Lee Y, et al. Exploring the potentials of sorghum genotypes: A comprehensive study on nutritional qualities, functional metabolites and antioxidant capacities. Front Nutri. 2023;10:1238729. https://doi.org/10.3389/fnut.2023.1238729

81. Makanjuola SB, Ogundaini AO, Ajonuma LC, Dosunmu A. Apigenin and apigeninidin isolates from the *Sorghum bicolor* leaf targets inflammation via cyclo-oxygenase-2 and

prostaglandin-E2 blockade. Int J Rheumatic Dis. 2018;21 (8):1487–95. https://doi.org/10.1111/1756-185X.13355

82. Agah S, Kim H, Mertens-Talcott SU, Awika JM. Complementary cereals and legumes for health: Synergistic interaction of sorghum flavones and cowpea flavonols against LPS-induced inflammation in colonic myofibroblasts. Mol Nutri Food Res. 2017;61(7):1600625. https://doi.org/10.1002/mnfr.201600625

83. Ravisankar S, Agah S, Kim H, Talcott S, Wu C, Awika J. Combined cereal and pulse flavonoids show enhanced bioavailability by downregulating phase II metabolism and ABC membrane transporter function in Caco-2 model. Food Chem. 2019;279:88–97. https://doi.org/10.1016/j.foodchem.2018.12.006

84. Salawu SO, Salimon YA. Evaluation of the effect of *Sorghum bicolor* aqueous extract on the haematological, renal and hepatic parameters in rats fed with low and high iron diet. Europ J Med Plants. 2014;4(7):783–93. https://doi.org/10.9734/EJMP/2014/7847

85. Espitia-Hernández P, Chavez Gonzalez ML, Ascacio-Valdés JA, Dávila-Medina D, Flores-Naveda A, Silva T, et al. Sorghum (*Sorghum bicolor* L.) as a potential source of bioactive substances and their biological properties. Crit Rev Food Sci Nutri.2022;62(8):2269-80. https://doi.org/10.1080/10408398.2020.1852389

86. Haikerwal M, Mathieson AR. The protein content and amino acid composition of sorghum grain. Cereal Chem. 1971;48:690–99.

87. WHO. Protein and amino acid requirements in human nutrition. World Health Organization Technical Report Series. 2007;(935):1.

88. Kent NL. Kent's Technology of cereals: An introduction for students of food science and agriculture. Elsevier; 1994.

89. Abd El Moneim MR, El-Beltagi H, Abd El-Salam SM, Omran AA. Biochemical changes in phenols, flavonoids, tannins, vitamin E, β-carotene and antioxidant activity during soaking of three white sorghum varieties. Asian Pacific J Tropical Biomed. 2012;2 (3):203–09. https://doi.org/10.1016/S2221-1691(12)60042-2

90. Przybylska-Balcerek A, Frankowski J, Stuper-Szablewska K. Bioactive compounds in sorghum. Europ Food Res Techn. 2019;245:1075–80. https://doi.org/10.1007/s00217-018-3207-0

91. Punia S, Kumar M, Siroha AK, Purewal SS. Rice bran oil: Emerging trends in extraction, health benefit and its industrial application. Rice Sci. 2021;28(3):217–32. https://doi.org/10.1016/j.rsci.2021.04.002

92. de Morais Cardoso L, Pinheiro SS, da Silva LL, de Menezes CB, de Carvalho CW, Tardin FD, et al. Tocochromanols and carotenoids in sorghum (*Sorghum bicolor* L.): Diversity and stability to the heat treatment. Food Chem. 2015;172:900-8. https://doi.org/10.1016/j.foodchem.2014.09.117

93. Paiva CL, Evangelista WP, Queiroz VA, Glória MB. Bioactive amines in sorghum: Method optimisation and influence of line, tannin and hydric stress. Food Chem. 2015;173:224–30. https://doi.org/10.1016/j.foodchem.2014.10.039

94. Chung IM, Yong SJ, Lee J, Kim SH. Effect of genotype and cultivation location on β-sitosterol and α-, β-, γ- and δ-tocopherols in sorghum. Food Res Int. 2013;51(2):971–76. https://doi.org/10.1016/j.foodres.2013.02.027

95. Leguizamón C, Weller CL, Schlegel VL, Carr TP. Plant sterol and policosanol characterization of hexane extracts from grain sorghum, corn and their DDGS. J Am Oil Chemists' Soc. 2009;86:707–16. https://doi.org/10.1007/s11746-009-1398-z

96. Hithamani G, Srinivasan K. Bioaccessibility of polyphenols from wheat (*Triticum aestivum*), sorghum (*Sorghum bicolor*), green gram (*Vigna radiata*), and chickpea (*Cicer arietinum*) as influenced by domestic food processing. J Agric Food Chem. 2014;62(46):11170–79. https://doi.org/10.1021/jf503450u

97. N'Dri D, Mazzeo T, Zaupa M, Ferracane R, Fogliano V, Pellegrini N. Effect of cooking on the total antioxidant capacity and phenolic profile of some whole-meal African cereals. J Sci Food Agric. 2013;93(1):29–36. https://doi.org/10.1002/jsfa.5837

98. Li M, Xu T, Zheng W, Gao B, Zhu H, Xu R, et al. Triacylglycerols compositions, soluble and bound phenolics of red sorghums, and their radical scavenging and anti-inflammatory activities. Food Chem. 2021;340:128123. https://doi.org/10.1016/j.foodchem.2020.128123

99. Luo X, Cui J, Zhang H, Duan Y. Subcritical water extraction of polyphenolic compounds from sorghum (*Sorghum bicolor* L.) bran and their biological activities. Food Chem. 2018;262:14–20. https://doi.org/10.1016/j.foodchem.2018.04.073

100. Sha X, Sun H, Li Y, Wu J, Zhang H, Yang R. The prolamins, from structure, property, to the function in encapsulation and delivery of bioactive compounds. Food Hydrocolloids. 2023;9:109508. https://doi.org/10.1016/j.foodhyd.2023.109508