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REVIEW ARTICLE

Red sorghum [*Sorghum bicolor* L. Moench]: A biochemical, nutritional hub and key food supplement - a review

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Abstract

Red sorghum (*Sorghum bicolor* (L.) Moench) stands out as a crucial dietary staple food, particularly in economically disadvantaged and food-insecure regions worldwide. Its diversity among landraces makes India a key hub for production. Red sorghum, renowned for its nutrient density and stress tolerance, holds immense potential as an alternate crop amidst climate change challenges. This review explores red sorghum's grain structure and nutritional profile, emphasizing its macronutrient and micronutrient composition, dietary fibre content, soluble sugars and bioactive secondary metabolites, including phenols, tannins and flavonoids. Understanding these aspects underscores the importance of red sorghum in addressing nutritional deficiencies and forecasting agricultural sustainability. Red sorghum offers many health benefits, particularly as a gluten-free alternative for individuals with celiac disease. Its rich phenolic compounds exhibit potential in combating carcinoma, while its starch composition, including slowly digestible starch, benefits diabetics with its low glycemic index. Combining sorghum with probiotic milk reduces oxidative stress in chronic renal disorders. Sorghum emerges as a versatile gluten-free ingredient rich in minerals and phenolic compounds, offering health benefits in various food products like cookies, RTE cereals, pasta and pet food. Additionally, exploring sorghum's genetic variations and health impacts paves the way for developing nutritionally superior varieties with robust agronomic traits.

Keywords

3-deoxy anthocyanin; condensed tannin; flavonoids; phenolics; red sorghum

Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is a primary dietary staple crop for some of the world's most economically food-insecure societies. It is the fifth most called -for cereal around the globe (1). Sorghum comprises 31 domesticated and 17 similarly related indigenous species in this family. Other historians have speculated that domestication may have occurred along the Egyptian Sudanese perimeter 5000-8000 years ago. It is the fifth most called-for cereal in terms of global demand. The USDA estimated that the sorghum output at the worldwide level was around 59,579 (1000 MT) (2023), which represents an 11.21% increase from the previous year around the globe. United States of America stands first in the global scenario, with production accounting for around 9.134 megatons, and India ranks 5th (4.39 megatons) or 7% of the total output (USDA, 2024). The central sorghum-growing states in India are Maharashtra, Karnataka, Andhra Pradesh and Tamil Nadu. Among the sorghum types, coloured sorghum occupies a

significant portion. Red sorghum attracted the attention of global researchers given its numerous benefits in the food, feed and pharmaceutical industries, apart from giving a substantial revenue to the farming community. Red sorghum has abundant bioactive compounds and is gluten-free. It's also known by other vernacular names, Sivappu cholam or Chen cholam in Tamil, Chuvappu cholum in Malayalam, Eruvu juar in Telugu and Laal jowar in Hindi. It can be used for animal feed, fuel, flour and beverages.

Nowadays, circumstances such as climate change and water shortage have made a look for 'alternate crops' around the globe (2). Besides stress tolerance, red sorghum was also asserted as a "nutrient-dense grain" due to its dietary profile richness compared to other cereal grains. The existence of 3-deoxyanthocyanin, a special phenolic pigment that resists high pH levels of 7-9 (3) a, makes it an excellent natural source in considerable quantities for synthetic food colouring in the brewing sectors, because of the dark red colour of the caryopsis, referred to as "bird proof" by people (4-5). In addition to being hailed as a highly nutritious food, sorghum is utilized in chefs' work of several cuisines internationally and in healthcare zones (6), as shown in Fig.1.

Even before the green revolution, millets and sorghum served as the principal food crops in India (7). Thenceforward, these crops took a back seat in area and production. Red sorghum is a well-attended backup for for the state of affairs and is generally suited to arid and semi-arid climates prevailing in the world (8). Plenty of diversity among the landraces made India a hub and secondary centre of origin. The development of prominent yielding hybrids and innovation in production technologies makes the conditions more affirmative for white grain sorghum than others. Market demand for red sorghum has been raised due to its luxurious nutritional profile (carbohydrates, dietary fibre and high nutrient composition). Based on these considerations, advancement in the production of productive stable red sorghum genotypes with rich nutritional profile is the need of the hour.

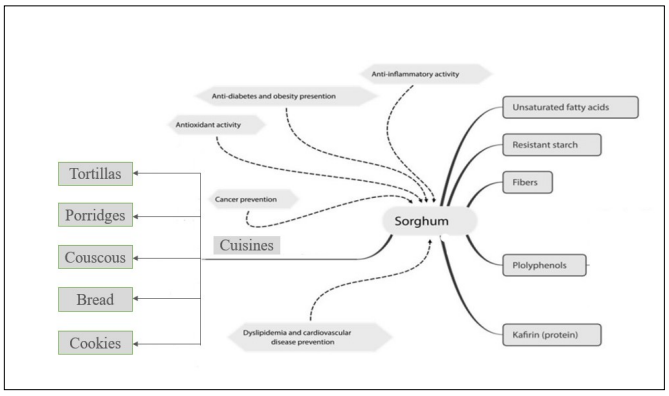


Fig. 1. Sorghum nutritional components, health benefits and cuisines.

Grain pattern and nutritional makeup of red sorghum

Grain structure

Red sorghum kernel, a naked caryopsis, includes three anatomical parts, covering the pericarp, germ (embryo and scutellum) and endosperm (9). Some other varieties have an added structure testa (Fig. 2) (10). Nonstarch polysaccharides, phenolic chemicals (phenolic acids, flavonoids and condensed tannins) and some vitamins (carotenoids) reside in the pericarp and testa of sorghum bran (11). Endosperm comprises proteins and carbohydrates containing minerals and vitamin B complex (12). The germ portion is predominantly comprised of lipids and proteins, but it also includes a lot of minerals and vitamins). Diversity in the colour of the pericarp may be extant (Fig. 3). The dominant genes R and Y (R* Y*) in sorghum are responsible for reddish pericarp, R*Y* red colour epicarp, R*yy white colour epicarp, rrY* lemon yellow colour epicarp, rryy white colour epicarp (13). Black sorghum is a unique kind of red sorghum because, as it ages, sunlight causes the red pericarp to become black and is characterized by high phenolic content (14). The anatomical element's proportion and chemical configuration of red sorghum rely on the genetic makeup and chronic conditions.

Macronutrient

Akin to additional cereals, carbohydrates are the principal macronutrient in red sorghum (15). The red sorghum carbohydrate encompasses dominant starch stored in the endosperm as granules (11). The primary components of red sorghum starch are amylose and amylopectin, although certain waxy sorghums may not have amylose or only have small amounts of it (16). The average starch content is 32.1 to 72.5 g per 100 g grain (17). The critical elements of sorghum nonstarch carbohydrates are arabinoxylans (glucuronoarabinoxylans) and β-glucans. The Arabinoxylan (pentosan), a complex polymer and pentosans exerts a mandatory role in bread making and contributes significantly to the overall quality of cereals (18). Protein is the second primary factor under macronutrients that prevails in sorghum (19). The protein present in red sorghum is

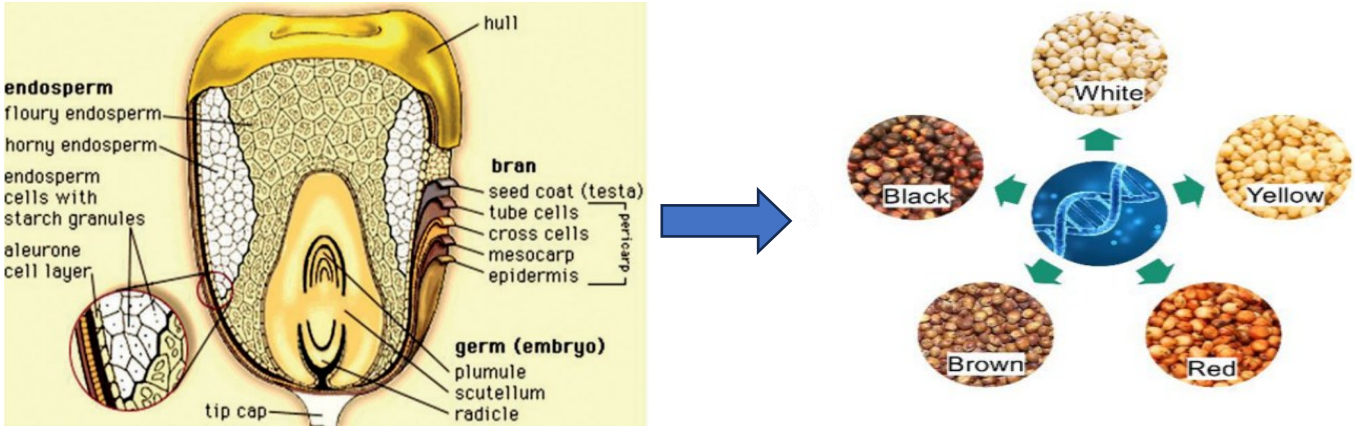


Fig. 2. Structure of Red Sorghum Kernel (96).

Fig. 3. Diversity in the colour of pericarp a) grey orange, b) dark brown.

of two types kafirin(α-, β-, γ - and δ-kafirin) and non-kafirin (globulins, glutelins and albumins). These hydrophobic proteins are kept in the endosperm in tightly coiled structures. (20). While looking at the composition of amino acids, there is a higher level of glutamic acid, leucine, alanine, proline and aspartic acid (21). The protein present in the sorghum is deficient in essential amino acids, such as methionine, lysine and cysteine (S-containing amino acid) (22). The grain protein content of red sorghum ranges from 4.4% to 21.1%, with a mean of 11.4% (23). The genes responsible for the grain nutrient profile and quality are in (Table 1). The lipid in red sorghum comprises unsaturated fatty acids, with polyunsaturated fatty acids being the most prevalent (24). Oil and protein content were shown to have a positive association, suggesting that the breeding program selects the traits simultaneously (25). Regarding genetics, in many investigations, gene activity was found to be both additive and dominant (26).

Micronutrient

Vitamins are indispensable nutrients for humans, as they cannot get rid of them in the body, so a consistent daily diet intake is necessary to uphold specific physiological functions (27). The vitamin composition in sorghum is similar to corn (28). Nevertheless, it is noteworthy that sorghum serves as a source of specific B-complex vitamins, including thiamine, riboflavin, niacin and pyridoxine, as well as fat-soluble vitamins such as D, E and K, which collectively include vitamin C and their composition (Fig. 4) is varied by both genetic and environmental variables, including soil and temperature (29-30). Minerals are inorganic substances that are present at minuscule scales for a multitude of functions (31). Millets generally cater to a loftier mineral density than other grains (32). Pursuant to research on sorghum grain, its mineral content is higher than maize and a

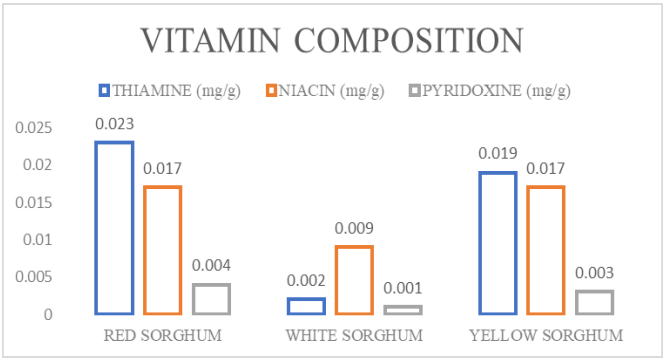


Fig. 4. Vitamin composition in various kinds of sorghum (31).

fraction of that of wheat, generating it a bit similar to millets (33). The grain botany, which possesses a pericarp, aleurone layer and germ, constitutes the primary source of vitamins and minerals such as (magnesium, iron, calcium, phosphorus and potassium) and (zinc copper), their composition depending on the kind, as shown in Fig. 5 (9,34).

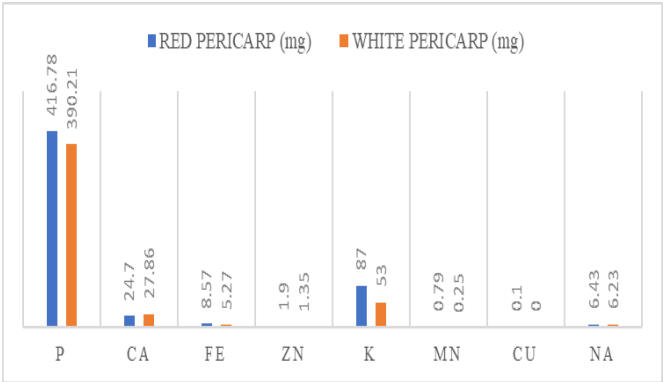


Fig. 5. Mineral composition in Red and White pericarp sorghum [P, Ca, Fe, Zn - (97). K, Cu, Mn, Na - (31).]

Table 1. Outlining genes for quality, their corresponding protein and phenotype

S.NO	GENE	PROTEIN	PHENOTYPE	REFERENCES
1	*AMY3*	Alpha-amylase debranching enzyme	Protein content	(80)
2	*Tannin1/B2*	WD40 protein	Testa	(81)
3	*Wx*	Granule-bound ADPglucose-glucosyl transferase	Endosperm texture	(82), (83)
4	*y1*	MYB domain protein	Pericarp color	(84)
5	*DGAT1*	Diacylglycerol O-acyltransferase 1	Crude fat	(85)

Dietary fibre (DF) is not a mono entity it includes a wide range of complex polysaccharides such as gums, cellulose and mucilage, each of which has different physiochemical and physiological properties found in the majority of plant-based meals in their native states (35,36). The soluble dietary fibre in cereals is around 8-20%, of which red sorghum holds DF content more than rice and is on a level playing field with wheat and other millets. It was also gathered that crude fibre in wheat and sorghum is 1.2 and 1.6g, respectively. Dietary fibre content in wheat and sorghum should be 11.4-17.2g and 9.7-14.3g (Fig. 6). Based on these studies, it was concluded that there is no critical difference between wheat-based and sorghum-based cereal food (37).

Figuring out the total soluble sugars present in sorghum is imperative because it plays an invaluable role in determining the taste of the prepared products (soluble sugars). The juice from the stalk is plentiful in soluble carbohydrates, including glucose, sucrose and fructose (soluble sugars). The amylase enzyme activity causes the fermentation of sugars into ethanol and carbon dioxide, which is widely consumed (38). Besides that, sorghum is gradually replacing barley in the brewing market to lower prices and boost their competition (39).

Bioactive secondary metabolites

The bioactive ingredients present in the sorghum include phenol, tannin and flavonoids (40) generated by the phenylpropanoid pathway. Secondary metabolites manifest how resilient plants are to biotic and abiotic stress.

Phenol

The first winding bioactive molecule witnessed in all the cereals and mainly in sorghum are phenolics (5), a significant quantity of which are found in the grain's outer coat. The content and profile of phenolics observed were found on par in sorghum than other cereals (41). The polyphenol in the sorghum is mainly associated with the pigmentation of the grain (21). The different phenolic compounds in red sorghum are overviewed in Table 2.

Tannin

Tannin (proanthocyanidins) is a secondary metabolite in sorghum that maintains defence action against predators and complications and is a potent radical scavenger (42). Certain healthy sorghum kinds have a wholesome inner integument, the site for condensed tannins (43). Even though they are found lacking in major cereals, they are present in sorghum varieties with pigmented testa and barley (44). The tannin content is dictated by the genes Tannin I and S (45). The tannin content in sorghum generally lies between 0.2 mg/g and 48.0 mg/g (46). They typically reduce the availability of other compounds, such as starches, proteins and minerals (47-49). The activity (bioavailability reduction) correlates with the amount of tannin and the polymerization degree (50). Their bioavailability is further increased during processing, mainly in dry heat at 95 °C for 20 min and 121 °C for 30 minutes (47). Red sorghums resist bird depredation, reduced preharvest germination and grain molding due to high tannin content.

Flavonoid

The flavonoids have their homes in red sorghum and are discovered in the grain's outer layers (51). The flavonoid concentration (3-deoxyanthocyanidins) is being impacted by the variation in the colour of the pericarp and the presence of testa (52) (3). There are three distinct classes of flavonoids (anthocyanins, flavones and flavanones) are present in massive quantities, of which anthocyanin (3- deoxy anthocyanin) being regulated by gene yellow seed 1 (53) alone corresponds to 79% of the total content (54) with a transformed structure, the absence of a hydroxyl group at position C-3 and more stable than previous structures (55). The various flavonoid compound in red sorghum is elucidated in Table 3. Furthermore, plant components, including leaves and sheaths, embrace up to 90,000 µg g^{-1} of 3-deoxy anthocyanidins (56). The bioavailability of sorghum anthocyanins in foods is correspondingly lower than other flavonoids and is impacted by the nature of sugar and its aglycone structure (57). The reduction in bioavailability is mainly due to spontaneous degradation under varied physiological circumstances or by microbial metabolism (58).

View on potential health benefits of red sorghum

Red Sorghum serves as a crop that's packed with an abundance of health rewards (Fig.7). Based on the reports from the U.S., celiac disease (CeDis) is hallmarked by an immunological reaction to gluten-containing suppers and becoming more common worldwide in the ratio of 1 in 250-300 and their dissemination to the kinsmen has been revealed (59-60). Hence,

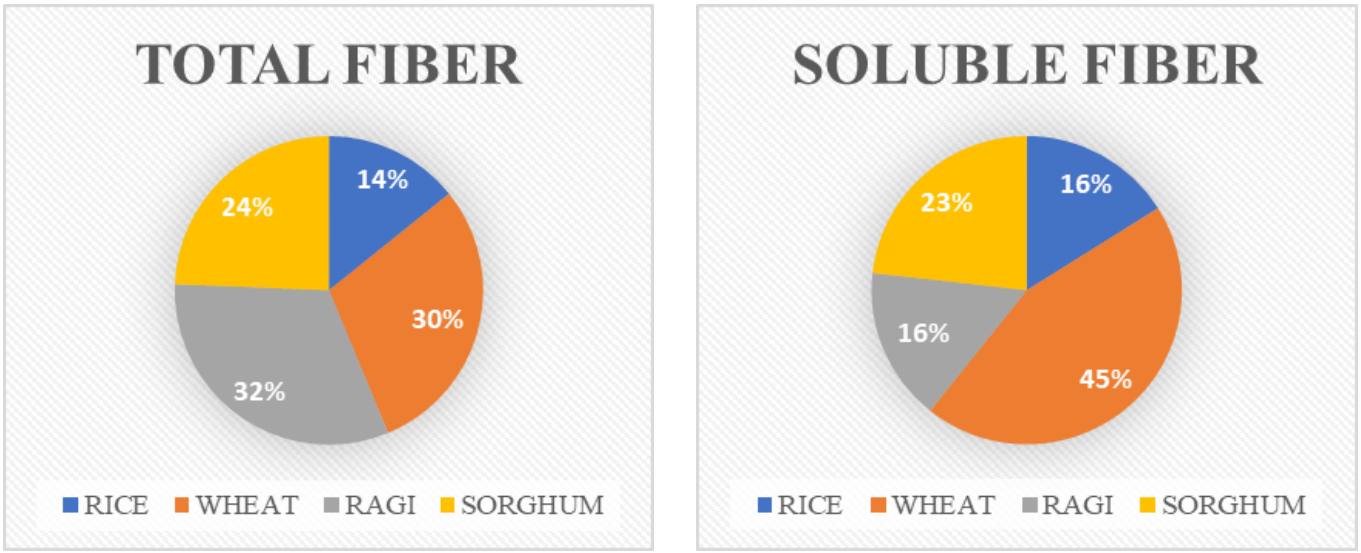


Fig. 6. Fiber content in various cereal grains (36).

Table 2. Various phenolic compounds in red sorghum

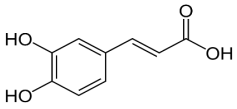
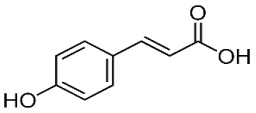
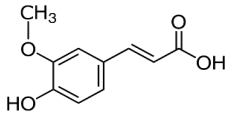
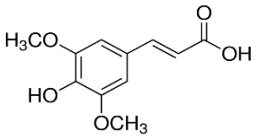
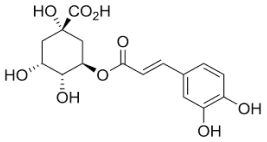
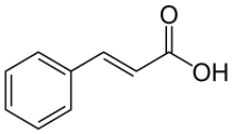
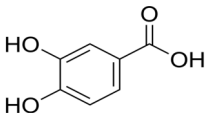
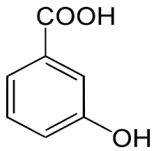
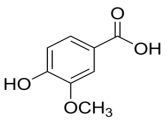
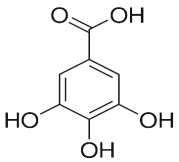
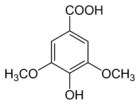
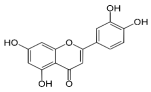
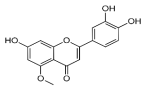
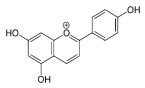
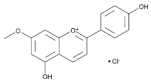
SOURCE	CONTENT (μg g^{-1})	COMPOUND	STRUCTURE	REFERENCES
Red sorghum	Soluble 0-523.02, Bound 1.32-161.11	Caffeic acid		(86)
	Soluble 90.71-172.44, Bound 193.25-489.18	p-Coumaric acid		
	Soluble 291.99-743.65, Bound 949.46-2210.92	Ferulic acid		
Red sorghum	10.5	Sinapic acid		(87)
	11.5	Chlorogenic acid		
	0	Cinnamic acid		
	83.5	Protocatechuic acid		
	19	p-Hydroxybenzoic acid		
	23	Vanillic acid		
	59	Gallic acid		
	5.5	Syringic acid		

Table 3. Various flavonoids in red sorghum

SOURCE	COMPOUND	STRUCTURE	CONTENT (μg g^{-1})	REFERENCES
Red sorghum	Luteolinidin		Soluble 20.39-57.14, Bound 0.06-0.15	(86)
	5-Methoxyluteolinidin		Soluble 2.23-6.04, Bound 0.-0.04	
	Apigeninidin		Soluble 4.76-13.04, Bound 0.01-0.04	
	7-Methoxyapigeninidin		Soluble 5.25-16.82, Bound 0.01-0.05	

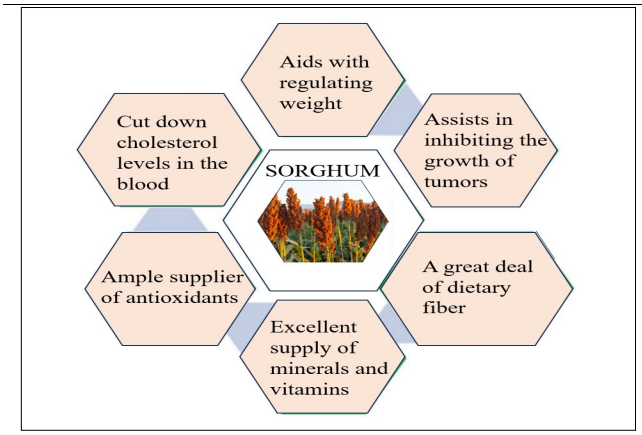


Fig. 7. Various Health Advantages of Red Sorghum

red sorghum, a gluten-free nourishment, acts as a great swap for food made with wheat (61-62). Grains of red sorghum are successfully utilized in preparing gluten-free bread, cakes and pasta (63-65). Flavonoids and diverse phenolic compounds have been documented in red sorghum and can dampen carcinoma proliferation (4). Their chemistry composition varies with different fractions (Fig. 8). A hundred grams of sorghum grain has an energy concentration that ranges between 296.1 and 356.0 kcal. (66).

The starch includes a substantial proportion of slowly digestible starch (SDS), slow digestibility is due to the robust interactions between condensed tannins, endosperm proteins and starch granules, which is particularly advantageous for diabetics (47). Red sorghum is reported to have a low glycemic index (GI) (67) and food with low GI has slower carbohydrate absorption and maintains fluctuation in blood glucose levels. In patients with chronic renal disorders, combining sorghum RTE cereals with unfermented probiotic milk has been demonstrated to lower oxidative stress and inflammation (68). Dietary fibres (Non-starch polysaccharides) in this food are

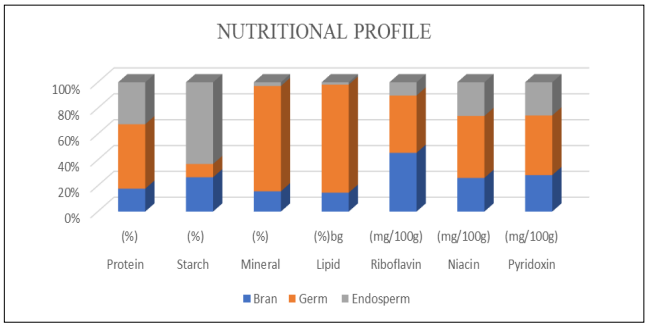


Fig. 8. Chemical Composition of Different Anatomical Parts

worthwhile for reducing blood glucose levels and avoiding colon cancer. Wu et al. innovated a sorghum grain tea by employing the entirety of the grain from a red sorghum variety alongside conventional processing methods such as soaking, steaming, and roasting. Tea had antioxidant properties and activities inhibiting α-glucosidase and α-amylase (11). The Red sorghum cuisine contains zinc, copper and manganese, which have antioxidant capabilities that hunt down free radicals and offset their detrimental impact (69).

Sorghum-Based Food Supplements

One of the most significant recent developments in the food industry using sorghum has been the production of novel, useful, healthful meals and beverages (Table 4). Sorghum has a great chance of being utilized as a gluten-free food component because of the rising need for gluten-free meals in Western and developing nations (70). It also renders a wealth of minerals and bioactive phenolic compounds that other foods might not possess (71). Studies have demonstrated a high phenolic content and antioxidant activity in cookies manufactured from red sorghum grain, which has antioxidant properties up to 20 times higher than wheat cookies (72). Ready-to-eat (RTE) cereals have become increasingly popular because they conveniently use crispy and crunchy textures. However, the main ingredients in these RTE products are often maize, wheat and oats. Sorghum could be a desirable choice for extruded RTE cereals. Research has indicated that the RTE breakfast cereals, derived from whole-grain red sorghum, are an excellent source of dietary fibre and phenolic compounds with potent antioxidant properties (73). Sorghum holds promise as a beneficial functional component in pasta, a widely consumed staple food crafted from durum wheat semolina worldwide. For instance, integrating red sorghum whole grain flour into pasta, substituting 20% to 40% of the semolina, notably boosted the levels of resistant starch, phenolic compounds and antioxidant properties (74,75). Muffins incorporated with sorghum possess elevated levels of resistant and slowly digestible starch (76). Adding red sorghum whole grain flour to Chinese steamed bread, replacing 30% wheat flour, notably increased the phenolic content and antioxidant activity (77). Besides its antinutritional effects and potential for reducing feed efficiency, sorghum is an alternative starch ingredient in pet food formulations (78). Including 0.5% red sorghum bran in pork pizza topping and dark chicken meat decreased lipid oxidation, mitigated rancid flavour, darkened colour and led to sorghum flavour (79).

Table 4. Various food supplements prepared from sorghum

S.NO	CUISINES	TYPE	BENEFITS	REFERENCES
1.	Cookies	Whole grain flour (Red)	It has a higher phenolic content, antioxidant activity, and satiety than wheat biscuits. Reduces oxidative stress and inflammation	(72),(88)
2	Egg noodles	Red sorghum flour	Differed physical quality from wheat noodles	(89)
3	Pasta	Whole red-grain flour	Improved food quality and health benefits	(90)
4	Animal feed	Grain (Red) with soluble	Improved animal health and production, reduces feed cost.	(91), (92)
5	Porridge	Decorticated grain	Slower stomach emptying and traditional African cuisine	(93)
6	Synthetic food colourant	3-Deoxyanthocyanidin	Resistance to pH, heat and acts as a natural water-soluble pigment	(94), (95)

Conclusion

Red sorghum is more beneficial than white sorghum in numerous ways. It is nutritious and rich in bioactive compounds, viz., phenol, flavonoids, tannins, total soluble sugars, etc. The bioactive composition profile has been unveiled as a factor in the sorghum's functional potential. Sorghum is a natural source of several B-complex vitamins, such as thiamine, riboflavin, niacin and pyridoxine. Hence, genotype selection and practical escalation need to be performed and the assemblage of bioactive compounds to maximize human health benefits needs to be ensured. Even though sorghum breeding has come a long way in the last few decades, more progress is still required in nutritional, biochemical and industrial aspects. Even though sorghum offers numerous health benefits, its utilization has diminished in regions where it historically served as the chief staple food. This decline is attributed to increased affluence, leading to a shift towards a more Westernized diet. Indeed, promoting and advertising the use of sorghum in food is essential, as its integration into the food system is still in its nascent stages. However, there has been notable progress in utilizing sorghum grain to create functional foods and incorporating sorghum or its components into various food products to enhance their quality and functionality. Sorghum is found to be an alternate crop for the changing global climate with water shortage and to fulfil the nutritional diet in India. Thus, red pericarp sorghum is an unexplored cereal with high nutritional profile. While considering the scenario far and wide, red sorghum landraces have huge diversity and are still being explored. Red sorghum landrace wants to get included in the breeding programme to develop stable, high-yielding types for the benefit of the farming community and pharmaceutical and industrial sectors since they have higher market prices than other sorghum types.

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Authors' contributions

The study's conceptualization and methodology were developed collaboratively by GA, SLN, ES and MLM. The field trial and data collection were carried out by SRK. The tasks of data curation, analysis, software development and manuscript preparation, including writing and editing, were undertaken by SRK, GA, SLN, ES and MLM. All authors contributed to and approved the final version of the manuscript, ensuring its accuracy and integrity.

Compliance with ethical standards

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