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Research Article

The Agrarian and Nutritional Potential of Sorghum (*Sorghum bicolor* (L.) *Moench*): A Review

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Abstract

Rapidly changing environment and increasing global temperature is fostering the need for sustainable agriculture. Promoting cultivation of alternative crop like sorghum which has lesser carbon footprint (5.94 Tg CE/ha) than wheat and rice (23.8 Tg CE/ha) and promotes resource conservation. Withal balanced nutrition and health benefits viz. cancer prevention, lowering cholesterol and fat absorption, delaying gastric emptying, sorghum possesses vital nutrients like proteins (11.5%), minerals (0.45-270mg/100g), vitamins, fiber (2.76%) and antioxidant phenolics (445 to 2,850 μg/g) and condensed tannins, carotenoids and 3-deoxyanthocyanidins (anthocyanin). Considered a prebiotic and being gluten free, foods can be developed using sorghum efficiently to cater the one percent of the world's population affected by celiac disease to combat deficiencies. Processing techniques such as soaking, blanching, germination, milling, decortication, etc. can bring about desired physical and chemical changes and enhance functionality of these grains. Thus, sorghum has the potential to contribute towards food and nutritional security while keeping in view sustainable agricultural practices.

Keywords: Carbon Footprint; Phenolic Compounds; Gluten-Free; Tannins; Processing

Introduction

Over reliance on limited number of cereal crops such as wheat and rice is creating a major impact on the global food and nutrition security. Pandemic of Covid-19 has added to this woe particularly in countries like India, Sudan, Ethiopia, Somalia, Yemen, Bhutan, and Sri Lanka, where the prevalent problem of malnutrition particularly among the vulnerable population could be accentuated by the combined effects of disease and hunger owing to the limited access of under-privileged population to food grains [1]. Hence, promoting the cultivation of alternative food crops by crop diversification is the need of the hour to address the prevailing situation [2]. Sorghum and millets, although under-utilized and marginally cultivated, have the potential to overcome food and nutritional insecurity. Sorghum (*Sorghum bicolor (L.) moench*), a coarse-grain cereal which belongs to *Andropogoneae* community of grass family *Poaceae* (*alt. Gramineae*) constitutes the attributes as tolerance to high level salinity. These characteristics cardinally increased attention towards this coarse grain which has been long labelled as poor man's crop and remained neglected with respect to its appropriate position in the food system and investment in research and development.

Regarded as king of millets, sorghum is native to tropical regions of Africa whilst also cultivated in India and China and possess international recognition of being cost-effective, owing to its low production cost and drought resistance property [4]. Presently, sorghum is cultivated according to various intended purposes such as grain (human consumption), sweet (syrup preparations), broom (making broom) and grass (feed and fodder) [5]. It is the fifth most produced crop in the world with a global production of approximately 58 million tons in 2019 (Figure 1) [6]. However, India is the fourth largest producer of sorghum and covered a production area of approximately 4.1mha with a production of 3.5 million tons in 2019 (Figure 2) and an average productivity of 953 kg ha-1 [7].

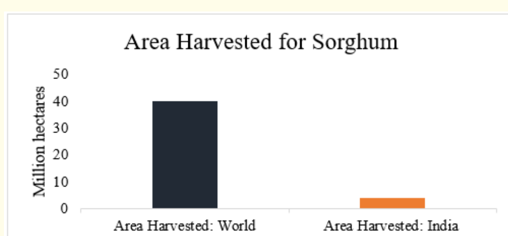

Figure 1: Area harvested for Sorghum in 2019 according to FAOSTAT [6].

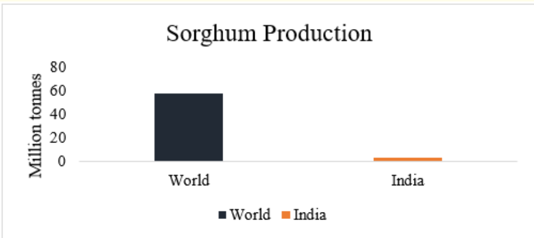

Figure 2: Production of sorghum grains in 2019 according to FAOSTAT [6].

Agrarian and environmental attributes

Agricultural sector has been considered to be one of the major contributors of greenhouse gases emission in the atmosphere [10]. According to Jain., *et al.* [11], wheat cultivation emits 'four tons of carbon dioxide equivalent per hectare'. This trend is further followed by cultivation of other staple crops such as rice and maize which has the potential to emit more than three tons carbon dioxide equivalent per hectare. However, cultivation of sorghum has the potential to rescue the current situation as its carbon footprints per unit area are reported to be lower (5.94 Tg CE/ha) in comparison to that of rice (23.75 Tg CE/ha) when studied over 50 years from 1960 to 2010 [12,12].

Besides, sorghum has high tolerance to biotic and abiotic stresses, thus, can be cultivated in semi-arid and arid regions with minimal land input. Research findings suggested that use of synthetic nitrogen fertilizers can be avoided by cultivating sorghum, since its roots has the ability to release a biological nitrification inhibitor which can decrease nitrification in the soil. The nitrification of soil decrease (50%) nitrogen availability for the plant [14]. Being a warm season crop, sorghum requires high temperature (27 - 30°C) for better germination and growth. The annual rainfall of about 400-800 mm is suitable during its cropping season, thus making it a less water intensive crop [15]. As reported by Paterson., *et al.* "[16], sorghum can bear sound cultivation on substantial vertisols of the tropical regions. However, its waterlogging tolerance become suitable for its growth in such areas. In addition, sorghum is resistant to attacks and damages caused by birds and insects and require minimal resources for their growth [17].

Structural and nutritional attributes

These spindle-shaped grains may possess variant colors such as white, red and yellowish-brown owing to the presence of various biochemical compounds on the kernel coat. The terms 'soft starch' designates the vitreous portion while 'hard starch' is labelled to the thick part of the grain's endosperm. Pericarp constitutes the outermost layer, followed by the endosperm of the grain with is a major storage organ while scutellum and embryonic axis supports the germ portion of the grain (Figure 3). However, the distribution of nutrients inside the grain majorly depends upon the conditions of its growth but mostly starch and proteins are stored in the endosperm while the presence of minerals and oils help the grain propagation and germination during its development. Presence of plethora of major nutrients and various biochemical compounds make sorghum the grains of high nutritional value [18]. It is endowed with about 73% of carbohydrates, 11.5% of protein and 3.5% fat with 2.76% crude fiber and 3.17% of ash making it a nutritionally sound choice for regular consumption [19,20]. Both sorghum grains and its flour are abundant in macro and micronutrients along with vitamins, minerals and other nutrients (Table 1).

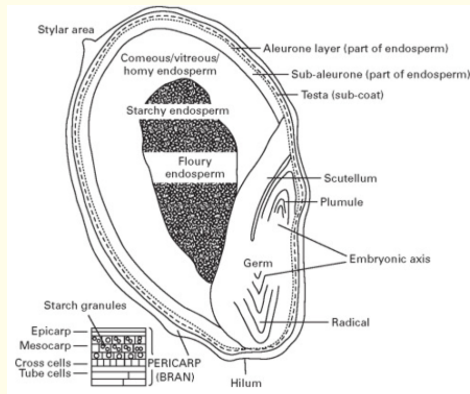

Figure 3: Structure of sorghum grain.

This nutri-cereal plays an important role in preventing and curing disease and illness and helps in regulating normal growth and development due to the presence of micronutrients and various bioactive compounds (Table 1). In virtue of this, [40] performed a comparative evaluation of antioxidant properties present in fiber-rich milled fraction obtained from various cereal grains including sorghum. It was revealed that coarse fractions had higher amount of insoluble fiber (17.26-20.93%) as compared to fine fractions (10.65-17.29%). In another research work by Abdelhalim., *et al.* [45], the chemical analysis of mineral content in Sudanese wild sorghum represented presence of Ca (50 to 270), P (113 to 198), Fe (1.18 to 1.91) and Zn (0.45 to 0.87) in mg/100g. Contrary to this, Tesie and Gebreyes [29] analysed the mineral composition of Ethiopian sorghum and revealed a higher content of same elements with Ca (79.85 to 319.6), P (112.554 to 367.97), Fe (2.262 to 14.08) and Zn (0.7 to 6.5) in mg/ 100g.

The characteristic color of the sorghum grains is a result of presence of various bioactive compounds such as phenolics, condensed tannins, carotenoids and 3-deoxyanthocyanidins , which is less susceptible to degradation, thus, is more stable. This property of 3-deoxyanthocyanidins is because of its lower susceptibility to nucleophilic attack as compared to other common anthocyanins, therefore making sorghum grains a rich source of functional foods [41,46,47]. The classification of sorghum grains on the basis of 3-deoxyanthocyanidins is depicted in figure 4.

The use of these coarse grains largely depends upon its varied color, juiciness, sugar content, etc. Those with a corneous yellow endosperm is preferred for human consumption attributed to the presence of carotene and xanthophyll [48]. Though, their red vari-

Nutrition composition of sorghum grain and sorghum flours				**References**
		Content in g/100g DW		
Components		Sorghum grains	Sorghum flour	
Macronutrients	Energy (kcal)	329	359	[21]
	Protein	9.61-11.67	8.43	[20,22,23]
	Fat	2.81-3.46	3.34	[21,24-27]
	Fiber	8.72-9.22	-	[24-27]
	Dietary fiber	6.7	6.6	[21]
	Carbohydrate	61.83-72.0	76.64	[17,20,24-27]
	Ash	1.67-1.88	1.32	[21,24-27]
Micronutrients	Phosphorus	0.346-0.385	0.278	[21,24,26,28,29]
	Potassium	0.251-0.363	0.324	[21,24,26,28,29]
	Calcium	0.086-0.291	0.012	[24,26,28,29,30]
	Sodium	0.082-1.35	0.003	[21,24,26,28]
	Magnesium	0.121-0.165	0.123	[21,26,28,29]
	Iron	3.36-17.38 $\times 10^{3}$	3.14×10^{3}	[21,26,28,29,31,32]
	Manganese	1.18-1.71 $\times 10^{3}$	1.26×10^{3}	[21,24,28]
	Copper	0.284-0.82 $\times 10^{-3}$	0.253×10^{-3}	[21,24,28]
	Zinc	1.67-9.61 $\times 10^{-3}$	1.63×10^{-3}	[21,23,24,26,28,31,32]
	Vitamin E	0.21-0.552 $\times 10^{-3}$	0.5×10^{-3}	[21,33,34,35]
	β-carotene	0.055-0.133 $\times 10^{-3}$	-	[33,35]
Bioactive Compounds	Total phenolics (GAE)	0.173-0.688	-	[26,33,36]
	Total flavonoids	48-63.8$\times 10^{-3}$	-	[33,34,36,37]
	Tannins	0.2-149$\times 10^{-3}$		[38,39,40]
	3-deoxyanthocyanidins	0.8-18.7 $\times 10^{-3}$	-	[34,36,41 -43]
	Phytate content	0.13-0.19	-	[24,26]
In vitro digestibility	*In vitro* protein digestibility (%)	54.1%	-	[39,44]
	In vitro starch digestibility (mg maltose/g)	34.8%	-	[44]

Table 1: Nutritional and Biochemical Composition of Sorghum (*sorghum bicolor L. moench*).

eties are often used in manufacture of beer in countries like Africa. Other varieties are also being used as sweet condiments in bakery industry while some popping varieties are popular for preparing healthy popped snacks.

However, some conventional processing techniques are generally being applied prior to consumption of sorghum grains to improve its palatablility, nutritive, and sensory characteristics [50]. In addition, germination and fermentation increases the antioxidants characteristics and reduces the phytate content of sorghum grains [51].

Soaking is one of the low- cost processing treatment applied to raw grains resulting in absorption of water by the grains, activating their enzymes and reducing the content of antinutritional factors [52]. According to Xiong., *et al.* "[52], soaking increased the total flavonoid content due to release of phenolic compounds as water penetrated the cell walls. However, Afify., *et al.* [32] reported that soaking grains for a long time led to leaching of water-soluble nutrients such as phenols, flavonoids and beta- carotene. In view of this, Akillioglu and Karakaya [54] suggested that longer duration of soaking may result in nutrient losses. Therefore, duration of soaking can be reduced by combining with other processing treatments such as germination to curb the losses.

Vashishth., *et al.* "[55] reported that soaking grains can activate exogenous or endogenous phytase enzymes which could further improve the *in vitro* mineral digestibility by 2 to 23%. In favour of this, Coulibaly., *et al.* [56] reported that mineral concentration and protein availability was enhanced while phytic acid concentration was reduced by soaking. Yet, another study performed on chickpea by Ertaş and Türker [57] revealed that soaking reduced the phytic acid concentration by 47.45 to 55.71% with an increase in soaking time from 2 to 12h.

An effective method for improving the bioactivity of grains, germination is a well-known biotechnical process for enhancing its nutritional value and palatability [58]. The enhanced flavour is

Figure 4: Classification of sorghum grains [49].

due to the formation of caramel-like odour yielding compounds like free amino acids and sugars, the precursor for flavour producing compounds. On the other hand, the reason of improved nutrition and palatability is the breakdown of certain antinutritional factors such as tannins, phytates, enzyme inhibitors Nkhata., *et al.* [59]. Garzón and Drago [60] performed germination on two cultivars of sorghum for 1, 2 or 3 days at 25 or 30°C and investigated the fate of γ-aminobutyric acid (GABA), total phenolic compounds (TPC), free amino acid profile (FAA) and antioxidant properties. The study reported an increase in GABA accumulation and free amino acid over time with time-temperature interaction. Among the phenolic compounds, ferulic acid was found in greater amounts. However, the study suggested a suitable combination of time and temperature interaction for desired germination to be 25°C for 3 days. Furthermore, Afify., *et al.* "[32], reported that germination resulted in reduced crude protein as compared to raw sorghum grains owing to leaching of soluble nitrogen, minerals and other nutrients. Although, a significant increase in *in vitro* protein digestibility and free amino acids were pronounced due to activation of enzymes. Apparently, the water absorption capacity of germinated grains was found to be significantly higher (1.38g/g) than raw grains whereas a significant decrease was observed in both loose and packed bulk densities (0.59 to 0.56 g/ml and 0.77 to 0.70 g/ml respectively) of germinated sorghum flour as reported by Ocheme., *et al.* "[61]. In addition, germination led to increase in the swelling (from 22 to 23.2 ml/g), foaming (from 14 to16.2%), and emulsion capacity (from 58.6 to 65.5%).

Puffing and roasting of sorghum grains is effective treatment to obtain grain and milled flour with improved starch characteristics [62]. Significant changes in starch degradability along with increase in *in vitro* protein digestibility was reported. Reduction of phytic acid upto 20-25% with improved glycemic index of 85 to 92 was also observed.

Similarly, effect of different thermal processing treatments applied to broomcorn millet was analysed by Azad et al [62]. A significant increase in the accumulation of total phenolic compounds (670 mg/100 g of ferulic acid equivalent) and total flavonoid content (391 mg/100 g of rutin equivalent) after roasting the whole millet while puffing was declared as third best treatment to enhance these bioactive compounds. The roasted millet showed a greater content of various phenolic compounds (syringic acid, gallic acid, 4-hydroxy benzoic acid, ferulic acid, sinapic acid, and catechin) when analysed chromatographically as compared to control grains. Roasting of millets also enhanced the antioxidant activity of the grains, thus declaring it as one of the safest thermal processing treatments for grains.

Sorghum in health and disease

The increasing public awareness regarding health and nutrition has created new prospects regarding the capability of phytochemicals (polyphenols and dietary fiber) and their health favourable traits. Therefore, an increasing demand to ascertain innovative sources of nutraceuticals and supplementary natural and nutritional ingredients possessing desirable functional traits is emerging.

Sorghum, a chief cereal of warm conditions, is endowed with essential nutrients like proteins, minerals, vitamins, and health promoters like fibers in addition to the presence of antioxidants and cholesterol-lowering waxes [65]. The grains are also loaded with starch and the composition of starchy endosperm is fundamentally different from that of wheat. Its endosperm is composed of cellulosic and non-cellulosic polysaccharides (mainly glucuronoarabinoxylans [GAX]). This water unextractable (insoluble) GAX of sorghum has a polymerization degree of approximately 1500 to 9300. Thus, they have somewhat high gelatinization temperature, leading to lower starch digestibility. In addition, the endosperm-protein matrix composed of cross-linked protein disulphide bond surrounding starch granules along with cell wall and tannins inhibits enzymatic hydrolysis of starch, thus reducing starch digestibility and making it a healthier choice among cereals. It is considered as a potential prebiotic which can boost viability of gut microflora and improve functionality of probiotics providing significant health benefits [64].

Recently, sorghum is receiving increased spotlight in combating diabetes as a dietary option [66]. Addition of sorghum bran to the diet may help protect against development of metabolic disease states such as obesity, type II diabetes, and inflammation by improving colonic microbiota [65]. Since the endosperm of sorghum contains resistant starch and its exposure to hydrothermal treatment leads to formation of cross linking (made of strong disulfide bonds) between kafirin (sorghum protein) and starch, the starch becomes resistant to digestion [67]. This property of sorghum reduces caloric intake, provides satiety and forms a low glycemic response which is desirable to prevent obesity and diabetes. In addition, the condensed tannins present in sorghum tend to make complexes with sorghum protein and starch and reduces its enteral absorption [68]. In a research study conducted by Stefoska-Needham., *et al.* "[69], it was revealed that consumption of sorghum whole grain biscuits by healthy individuals was reported to provide satiety for longer duration whole wheat biscuits.

Kim., *et al.* "[70] demonstrated the inhibitory effect of 'sorghum phenols' against digestive enzymes such as α- glucosidase, human salivary and porcine pancreatic α-amylase while Chung., *et al.* "[71] reported an increase in serum insulin levels by the same. However, Links., *et al.* "[72] suggested that the inhibition of digestive enzymes could be considered as the beginning of antidiabetic mechanism and to prevent glucose digestion. According to Kim and Park [72], the sorghum phenolic extracts administration to streptozotocin-induced diabetic rats showed a significant reduction in their plasma glucose levels. Sorghum lipids were established to regulate the homeostasis of cholesterol in the body, thus promoting the cardiovascular health [67]. Research studies have revealed that the administration of lipids extracted from sorghum grains to hyperlipidemic rats significantly reduced their plasma cholesterol and triacylglycerol levels [71,72].

Nonetheless, an approximately one percent of the world is affected by celiac disease and a significant increase of the condition is observed due to the lack of early diagnosis. The only treatment for people with celiac problem is adherence to gluten free foods for life time. Ofosu., *et al.* "[37] had reported that sorghum proteins do not cause autoimmune diseases and thus recommended it to be safe for consumption by celiac patients. However, gluten free food products can be developed using sorghum efficiently which not only can provide satisfaction to celiac patients but can also help to combat malnutritional deficiencies owing to disease [74].

In vitro and animal research studies performed to analyse the nutritional potential of sorghum grains have claimed it to be an excellent source of bioactive compounds renowned to inherit health promoting properties. Oxidative stress can be caused in the body due to imbalance created between free radicals and antioxidants due to poor lifestyle. This situation has the potential for development of chronic degenerative diseases such (obesity, cardiovascular diseases, diabetes, dyslipidemia, cancer). In light of this, Wu., *et al.* [75] investigated the cellular antioxidant activity level in sorghum incorporated Chinese steam bread using cell culture protocol and showed a significant increase in the levels of same. High proportion of phenolic acids, flavonoids (3-deoxyanthocyanidins), condensed tannins, stilbenes and lignins produced by the phenylpropanoid pathway contributes to its high phenolic compound profile. According to Girard and Awika [76] sorghum grains contain an abundant concentration (445 to 2,850 μg/g) of phenolic acids [77]. The phenolic compounds isolated from sorghum grains provides protection against various degenerative diseases [73,78].

Besides, these phenolic compounds have the ability to induce the production of some enzymes in the body responsible for converting the harmful reactive oxygen to non-toxic compounds, thus reducing the risk of oxidative stress [79,80]. Among the phenolic acids, the most abundant is ferulic acid (100 to 500 μg/g in the grain) which can form up to 90% of the total bound phenolic acids [81]. Another powerful phenolic compound present in sorghum is 3-deoxyanthocyanidins, reported to increase NADH:quinone oxyreductase (NQO) activity in some cancer cells, thus, prevents accumulation of cancer cells in body [79]. 3-deoxyanthocyanidins are a rare subclass of anthocyanins with apigeninidin and luteolinidin aglycones being the main 3-deoxyanthocyanidins in sorghum [67]. With a concentration of 200 to 4,500 μg/g, 3-deoxyanthocyanidins are one the most abundant flavonoid in sorghum [32,76]. However, red and black sorghum are rich in 3-deoxyanthocyanidins with a reported efficacy against cancer cells. However, sorghum with white pericarp and low 3-deoxyanthocyanidins concentrations have also been reported to show similar effects in the body [80].

Also, condensed tannins present in sorghum are the most powerful antioxidants as reported by Tian., *et al.* [82]. Since these tannins are not absorbed by the body, they are capable of forming complexes with other molecules and can serve as free radical terminator. Persistent oxidative stress can lead to inflammation and prolongation of the same may lead to chronic degenerative diseases. Inflammation being an immunity response against foreign invasion in the body leads to generation of number of pro inflammatory chemicals such as such as interleukin (IL), cyclooxygenase (COX)-2, tumor necrosis factor (TNF)-α, and prostaglandin E2 (PG-E2) [82]. Although, phenolic compounds present in sorghum grains have the potential to curb the production of these chemicals [84]. According to Agah., *et al.* [85],Funakoshi-Tago., *et al.* [86],Wölfle., *et al.* [87], phenolic acids, flavone apigenin and luteolin were reported to inhibit the production of COX-2 enzyme, TND-α and transcription factor i.e., nuclear factor kappa B (responsible for activation of pro-inflammatory compounds), respectively.

In addition, Shim., *et al.* [82] had reported strong inhibitory effects against COX-2, IL-1β, and TNF-α of phenolic compounds extracted from black sorghum bran. A similar study by Stefoska-Needham., *et al.* [88] demonstrated the effect of consuming sorghum whole-grain biscuits over 12 weeks by overweight adults. The results showed significant reduction in the pro-inflammatory compounds like IL-1β, IL-6, IL-8, and TNF-α. Furthermore, the phenolic extract of sorghum bran was also reported to inhibit 'hyaluronidase enzyme' (an enzyme involved in joint inflammation).

Conclusion

It can be concluded that this overlooked grain has the potential to contribute towards food and nutrition security particularly in the drought-prone areas of the world. Since sorghum grains have diverse biological activity, advanced researches including clinical investigations need to be explored.

Currently, researchers are trying to discover the mechanisms in the area of health effects by sorghum in the body, while others are making efforts to develop novel food products using sorghum to attain maximum health benefits and popularize its consumption among masses. Before transforming the whole grains into novel food products, there is a need to expose the raw grains to hydrothermal and other processing treatments.

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