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REVIEW ARTICLE

Integrative approaches in sorghum improvement: From nutritional security to industrial sustainability

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Abstract

Sorghum [*Sorghum bicolor* (L.) Moench] is a vital, climate-resilient C4 cereal crop that is gaining increasing recognition for its wide industrial potential, yet it remains underutilized compared to maize. This review explores the diverse applications of sorghum and highlights genetic advancements that have contribute to its trait improvement, especially in sustainable agriculture, bioenergy and bioproducts. Sorghum's high-quality grain, substantial biomass yield and efficient ethanol conversion position it as a promising crop for biofuel production. Additionally, its lignocellulosic biomass serves as a valuable feedstock for biodegradable polymers, resins and other eco-friendly materials, supporting global sustainability goals. The crop's inherent tolerance to drought and heat, along with minimal input requirements, makes it suitable for low-resource farming systems, particularly in arid and semi-arid regions. Furthermore, sorghum plays an essential role in food security, serving as a staple food crop in different regions. Advances in molecular breeding, genetic engineering and biotechnology have enabled the development of sorghum varieties tailored for industrial applications, improving traits like biomass composition, stress tolerance and sugar content. Despite its potential, challenges such as climate-induced stress, pests and limited market development persist. Addressing these through collaborative research policy support and innovation can enhance sorghum's role in climate-smart agriculture and industry. This review underscores sorghum's adaptability and growing importance in promoting sustainable, resilient agricultural and industrial systems.

Keywords: bioenergy; bioproducts; genetic enhancement; industrial uses; sorghum types

Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is a climate-resilient C4 cereal crop that feeds over 500 million people worldwide, predominantly in semi-arid and tropical regions (1). Originating in northeastern Africa, sorghum serves as a staple food and a lifeline for millions of smallholder farmers due to its inherent drought and heat tolerance, minimal input requirements and adaptability to marginal environments (1). As a member of the Poaceae family and the Andropogoneae tribe, sorghum exhibits exceptional photosynthetic efficiency, enabling it to thrive under high temperatures and low moisture conditions (2, 3).

Globally, sorghum is cultivated on approximately 40 million hectares, producing over 61 million metric tonnes of grain annually, making it the fifth most-produced cereal after wheat, maize, rice and barley (4, 5). Major producers include the United States, Nigeria, India, Mexico, Sudan and Ethiopia, with significant contributions from China, Argentina, Brazil and Niger (6). In the United States, large -scale mechanised cultivation, particularly in Kansas and Texas, is driven by its use as animal feed and biofuel (7). In West Africa, sorghum remains a critical food security crop, while in India, locally known as "jowar", it is integral to diets and farming systems in Maharashtra, Karnataka, Madhya Pradesh, Rajasthan, Telangana, Andhra Pradesh, Gujarat and Uttar Pradesh (8).

Despite its significance, sorghum farmers face numerous challenges, including unpredictable monsoon patterns, pest infestations (shoot fly, stem borer, midge and grain mould), soil degradation and limited market access (1, 5). Competition from other cereals such as maize and wheat, coupled with price fluctuations, further undermines its economic viability (1, 5).

Sorghum's culinary versatility underpins its widespread consumption. As a gluten-free grain, it is processed into porridge, flatbreads, couscous and beverages across Africa and Asia (4, 7). Traditional foods like roti, bhakri, kisra, injera and mantou, as well as porridges such as sankati, bogobe and ugali, reflect its centrality in regional diets (8). Its high starch content also makes sorghum a valuable industrial raw material (9). In the biofuel sector, sorghum's fermentable sugars are critical for ethanol production, particularly in sweet sorghum varieties such as SSV 84, which are specifically bred for high stalk sugar content and enhanced bioethanol yield. (5). For instance, India achieved a 12 % ethanol blending rate in gasoline in 2023, targeting 20 % by 2025-26, with projected ethanol production reaching 6.35 billion litres in 2024 (5). However, constraints such as inconsistent feedstock supply, inadequate processing infrastructure and policy fluctuations hinder the full realization of biofuel targets (5).

Beyond food and biofuel, sorghum offers potential in biodegradable materials, pharmaceuticals and nutraceuticals due to its bioactive compounds such as 3-deoxyanthocyanidins, ferulic acid, tannins and flavonoids like luteolin and apigenin, which possess antioxidant, anti-inflammatory and anticancer properties. (4, 9). Its lignocellulosic biomass is a promising feedstock for eco-friendly polymers and resins, contributing to sustainability goals (9).

Despite these diverse applications, sorghum remains underutilised compared to major cereals like maize, largely due to limited investment in breeding for industrial traits, value chain development and market integration. Addressing these gaps through genetic improvement, biotechnological interventions and supportive policies can enhance sorghum's role in climate-smart agriculture and sustainable industries (1, 5).

Therefore, the objective of this review is to analyse global sorghum production trends and identify key producing countries (10), as well as evaluate its nutritional benefits and diverse utilization pathways (4, 8).

Additionally, it aims to review recent advances in genetic improvement and biotechnological interventions (1-3) and to identify existing research gaps and future directions to optimise sorghum's role in enhancing food security, strengthening climate resilience and promoting sustainable industrial development (1, 5).

Global sorghum production trends: key producers and growth patterns

Sorghum is a vital cereal crop cultivated across diverse agro-ecological regions for food, fodder and industrial uses. Understanding global production trends is crucial for assessing regional productivity patterns, market dynamics and for informing future agricultural strategies related to climate adaptation, food security and the emerging bioeconomy. Globally, sorghum is produced on approximately 40 million hectares, with an annual production of over 61 million metric tonnes, ranking it as the fifth most-produced cereal after wheat, maize, rice and barley (5). Major producers include the United States, Nigeria, India, Mexico, Sudan and Ethiopia, collectively accounting for the bulk of global output (11).

While the United States remains the largest producer, particularly for animal feed and bioethanol industries (6, 10), countries such as Nigeria and India utilise sorghum primarily as a food staple (5, 7, 9). Recent trends indicate that countries like Brazil and Ethiopia are showing significant production increases due to expanded cultivation areas and improved varieties (5), whereas traditional producers such as China and the USA have experienced marginal declines attributed to shifts towards other high-value crops and changing agricultural policies (11). These dynamic trends underline the importance of targeted research, policy interventions and market development to harness sorghum's full potential in ensuring food security, supporting livestock industries and driving bio-based industrial growth in both developed and developing countries (1).

Global sorghum production is dominated by the United States, while countries like Nigeria and India rely on it as a staple food. Recent growth in Brazil and Ethiopia contrasts with declines in China and India, reflecting shifting cultivation patterns and policies. Table 1 summarizes production levels and growth trends among the top producers (10, 11).

Table 1. Top sorghum producing countries and their growth trends

Country	Production (million metric tons)	Growth rate (%)
United States	8.18	Leading producer
Nigeria	6.7	Moderate growth
Sudan	5.0	Stable
India	4.5	Declining
Mexico	4.2	Slow growth
Ethiopia	3.8	Increasing
Argentina	3.6	+ 9.32 %
Brazil	2.9	+10.58 %
Australia	2.5	Stable
China	2.1	Declining
World total	~61	-

Nutritional benefits of sorghum

Typically, sorghum grains contain 68 %-75 % carbohydrates, 10 % -12 % protein, 3 %-4 % fat and 1.5 %-2.5 % minerals, providing approximately 329 kcal per 100 g (12,13,14). It is an important source of minerals such as iron (4.4 mg), magnesium (165 mg), phosphorus (289 mg), as well as B-complex vitamins, which collectively support energy metabolism, bone health and overall physiological functions (14, 15). Its high dietary fibre content aids digestion and promotes gut health (16). Additionally, sorghum is naturally gluten-free, making it an ideal grain alternative for individuals with celiac disease or gluten intolerance (17).

Beyond its macronutrient and micronutrient composition, sorghum is abundant in bioactive compounds such as phenolic acids (e.g. ferulic acid, *p*-coumaric acid), flavonoids (e.g. luteolin, apigenin) and tannins, which possess antioxidant properties that contribute to reduced oxidative stress, anti-inflammatory effects, improved cardiovascular health and potential anticancer activities (18, 19, 20). However, the presence of anti-nutritional factors such as tannins and phytates can reduce the bioavailability of certain minerals, particularly iron and zinc (21). Breeding efforts targeting low-tannin varieties and food processing techniques like decortication, fermentation and germination have been employed to mitigate these limitations and enhance nutrient availability (21).

Overall, sorghum's diverse nutritional profile and functional bioactive compounds underscore its significance in promoting nutritional security, supporting health and serving as a promising ingredient in the development of functional foods and nutraceuticals (22). Sorghum grain provides essential nutrients including protein, starch, minerals and vitamins, but also contains anti-nutritional factors such as tannins and phytic acid, which influence nutrient availability. The compositional ranges are shown in Table 2 (23).

Types of Sorghum

Sorghum is a versatile crop with various types cultivated for food, feed, fodder and industrial applications. The four major types are grain sorghum, forage sorghum, sweet sorghum and biomass sorghum, each with unique traits and uses.

Grain sorghum

Grain sorghum is primarily cultivated for human consumption and livestock feed. It is rich in carbohydrates (68 %-75 %), protein (10 %-12 %) and micronutrients such as iron, zinc and magnesium, with phenolic-rich bran offering antioxidant properties (14, 16, 18, 19, 24).

Table 2. Nutritional and anti-nutritional composition range of sorghum grain

Constituent	Range
Protein (%)	4.4-21.1
Water soluble protein (%)	0.3-0.9
Lysine (%)	1.06-3.64
Starch (%)	55.6-75.2
Amylose (%)	21.2-30.2
Soluble sugars (%)	0.7-4.2
Reducing sugars (%)	0.05-0.53
Crude fiber (%)	3.4
Fat (%)	2.1-7.6
Ash (%)	1.3-3.3
Minerals (mg/100 g)	
Calcium	11-586
Phosphorous	167-751
Iron	0.9-20.0
Vitamins (mg/100 g)	
Thiamine	0.24-0.54
Niacin	2.9-6.4
Riboflavin	0.1-0.2
Anti-nutritional factors	
Tannin (%)	0.1-7.22
Phytic acid (mg/100 g) as phytin phosphate	875-2211.9

Sorghum exhibits diverse morphological traits that underpin its adaptability to different environments. The key plant structures that influence productivity and utilization is illustrated in Fig. 1. Grain colour influences its phenolic profile, with white and yellow types having low tannin content, while red, brown and black types possess higher phenolic compounds such as 3-deoxyanthocyanidins and condensed tannins (20-22). These bioactive compounds enhance its potential as a functional food ingredient (4, 19). Industrially, grain sorghum is used for producing bioethanol, high-fructose syrups, biodegradable plastics and adhesives, with varieties like TX430 and BTx623 preferred for their high starch yields (7). Additionally, its gluten-free flour is increasingly popular in health-conscious markets (4, 7).

Forage sorghum

Forage sorghum is valued for its high biomass yield and drought tolerance, making it a suitable alternative to maize silage in water-limited regions (25, 26). Key breeding traits include plant height, tillering, crude protein content, fibre composition and digestibility (27, 28). The development of brown midrib (BMR) lines has improved forage digestibility by reducing lignin content, benefiting livestock productivity (29). Forage sorghum hybrids such as Sorghum × Sudan grass are widely used for silage, grazing and biogas production, contributing to circular farming and sustainable livestock systems (30, 31).

Sweet sorghum

Sweet sorghum, known for its high sugar-rich stalk juice (°Brix 15 %-20 %), is a multipurpose crop used for food, fodder, fuel and liquor. It is commonly cultivated in countries such as India, China, the United States, Brazil and parts of sub-Saharan Africa, where it is valued for its adaptability to semi-arid conditions and potential for bioenergy production. (32, 33). It produces ethanol that is cleaner than molasses-based ethanol and requires less water compared to sugarcane, making it a viable bioenergy crop in semi -arid regions (34). Sweet sorghum is valued as a multipurpose crop that contributes to both food and energy sectors. Fig. 2 outlines the major pathways of its utilization across food, feed and biofuel industries.

Its juice is processed into syrup, jaggery and alcoholic beverages, while the bagasse serves as fodder and fuel. On an industrial scale, sweet sorghum is cultivated in countries like India and China for bioethanol production and commercial syrup processing, highlighting its versatility in both food and energy sectors. (35, 36). Varieties such as CSV 19SS and SSV 84 are widely cultivated for their high biomass and juice yields, supporting India's ethanol blending targets and promoting sustainable biofuel production (32, 37).

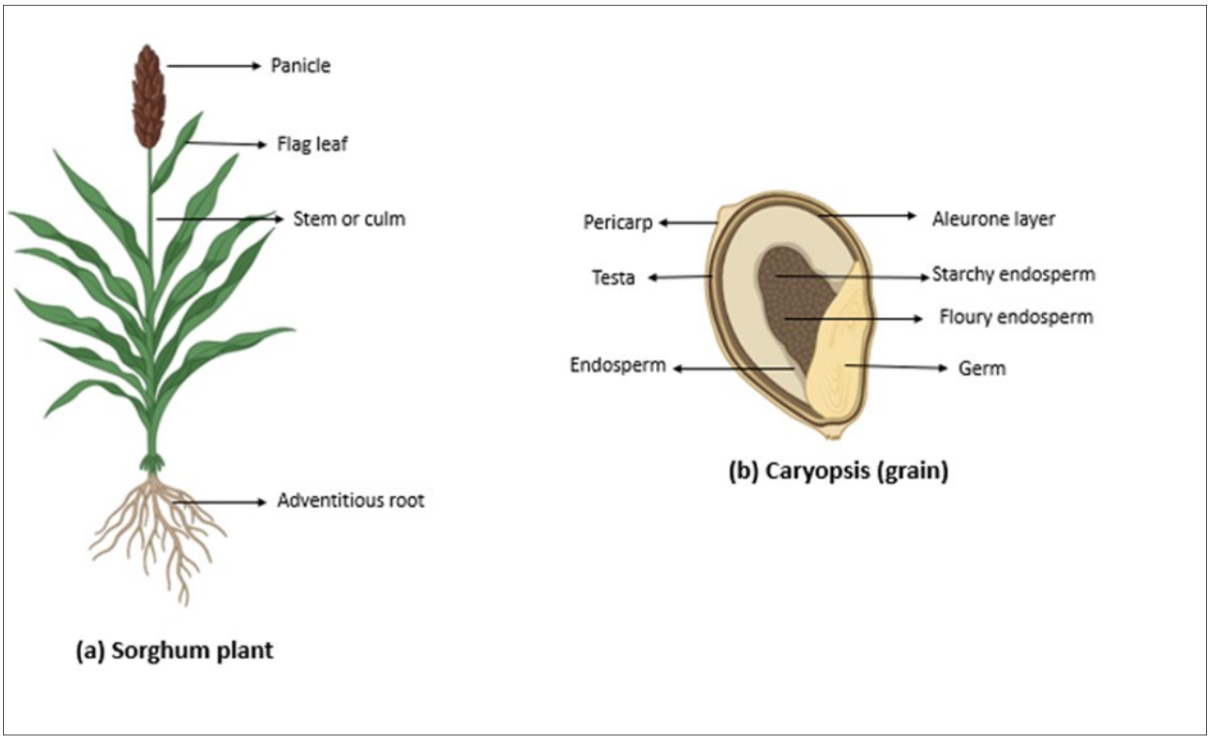

Fig. 1. Morphological features of sorghum (source: Biorender).

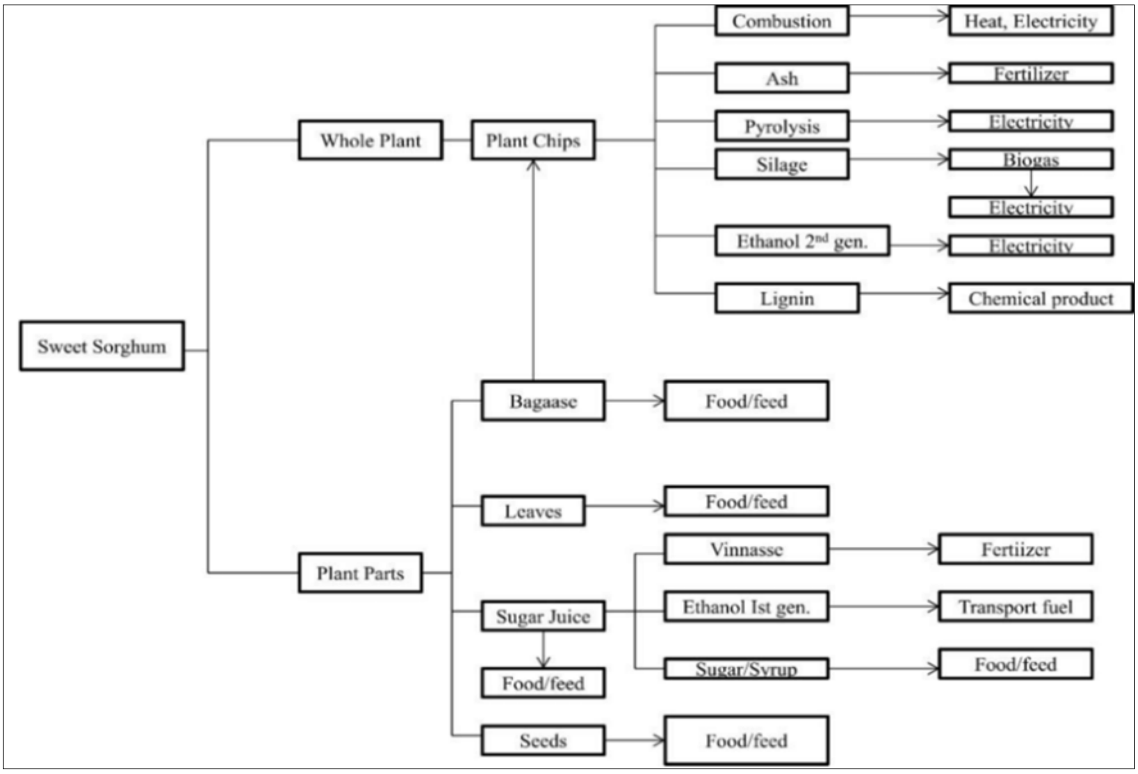

Fig. 2. Utilization pathways of sweet sorghum for food, feed and bioenergy.

Biomass sorghum

Biomass sorghum is bred specifically for lignocellulosic biomass production, reaching heights up to 20 feet and offering high yields suitable for bioenergy and industrial uses (38, 39). Its stem and leaves are processed into biofuels, biodegradable materials and paper pulp, contributing to low-carbon and circular economies (40, 41, 42). Varieties like FS-5 and Silage King combine high biomass accumulation with drought resilience (40). Breeding focuses on enhancing plant height, stem diameter, cellulose content and harvestability traits to improve biofuel conversion efficiency (41- 44).

Starch sorghum (waxy sorghum)

Waxy sorghum, rich in amylopectin, is used in the food industry as a thickening agent due to its gel-like texture and stability (45, 46). It is also valued in non-food industries for adhesives and biodegradable plastics (46, 47). Its starch properties enhance bioethanol production efficiency, while its high digestibility benefits brewing and livestock feed (48, 49). Inbred sorghum varieties exhibit higher amylopectin content and crystallinity, making them ideal for applications requiring slow starch digestion and prolonged energy availability, such as functional foods for glycemic control and endurance nutrition (49).

Popping sorghum

Popping sorghum is traditionally consumed in Africa and Asia as a nutritious snack (45, 46). Its grains "pop" when heated, producing small, crunchy kernels with a nutty taste (45). This type is rich in dietary fibre, antioxidants and polyphenols, especially in coloured varieties, contributing to gut health and reduced oxidative stress. Key polyphenols identified in sorghum include 3-deoxyanthocyanidins, phenolic acids such as ferulic acid and caffeic acid and flavonoids like luteolin and apigenin. (13, 21, 24). Breeding priorities include improving poppability percentage, expansion volume, kernel uniformity and aroma (45). Recent ICRISAT studies have identified 36 promising popping lines for commercial development, aiming to popularise it as a gluten-free, allergen-friendly snack in health-conscious markets (46). Additionally, popped sorghum flour is used in snack bars, cereals and traditional sweets blended with jaggery for enhanced nutrient density and taste (9, 45).

Vegetable (hurda) sorghum

Vegetable sorghum, locally known as "hurda" in Maharashtra, is harvested at the soft dough stage when grains are tender and sweet (50). It is consumed roasted, boiled or steamed, similar to baby corn, offering high energy, dietary fibre, B vitamins, calcium and magnesium (50). Recent breeding programs focus on improving tenderness, sweetness, biomass yield and stress tolerance to expand its cultivation beyond traditional areas (47, 48). Semi-mature grains have higher antioxidant levels than dried grains, contributing to their role in school feeding programs and community nutrition interventions targeting micronutrient deficiencies and food security in resource-limited settings (49-51).

Vitamin A / biofortified sorghum

Biofortified sorghum enriched with provitamin A carotenoids is being developed to combat vitamin A deficiency, especially in Sub -Saharan Africa (52). Varieties like ICSB 52 and PVK 801 deliver higher beta-carotene content while maintaining agronomic performance (52, 53, 54). Breeding uses QTL mapping and GWAS to integrate high-carotenoid genes with traits like grain size, pest resistance and processing stability (54, 55). These varieties are incorporated into fortified flours, porridges and infant cereals to address hidden hunger (56). Research also explores improving carotenoid retention post-harvest through protective processing methods (57).

Brown midrib (BMR) sorghum

BMR sorghum is characterised by reduced lignin content due to mutations in *bmr* genes (*bmr6, bmr12, bmr19*), resulting in enhanced digestibility for livestock and improved cellulosic ethanol yield (58, 59). Varieties such as BMR-106, BMR-12 and SPV

2451 combine low lignin with acceptable yields, making them ideal for silage in dairy and beef production (57-59). However, reduced lignin may weaken stem strength, increasing lodging risk and pest susceptibility, thus breeding focuses on balancing digestibility with agronomic robustness (56, 59). Recent gene-editing tools like CRISPR/Cas9, are being explored to precisely target lignin biosynthesis pathways for optimal forage quality (59).

Tannin-free sorghum

Tannin-free sorghum varieties enhance protein digestibility and mineral bioavailability, making them ideal for weaning foods, monogastric animal feed and functional flours (57, 58). Varieties like PVK 801 and AKJ 1 lack condensed tannins, improving organoleptic qualities and cooking efficiency (9, 58). However, absence of tannins increases susceptibility to bird and pest damage, requiring integrated pest management (58). Industrially, tannin-free sorghum is used in biscuits, noodles, malt beverages and gluten-free ready-to-eat mixes due to better starch gelatinization and improved taste (9, 58).

Quick-cooking sorghum

Quick-cooking sorghum types, such as Parbhani Moti and Phule Vasudha, possess high amylopectin content and low gelatinization temperatures (~55 °C), enabling faster cooking suitable for instant cereals, porridges and extruded snacks (58, 57). Breeding aims to improve grain hydration, soften endosperm texture and reduce phytate levels to enhance mineral bioavailability (59, 60). These varieties cater to urban markets, school meal programs and emergency nutrition kits where rapid preparation and nutrient density are essential (59).

Aromatic sorghum

Aromatic sorghum varieties possess a fragrance similar to Basmati rice due to suppressed *BADH2* gene expression, enhancing their appeal in specialty ethnic foods and beverages. To preserve this aroma, careful post-harvest handling such as gentle drying at low temperatures and minimal milling is essential to prevent loss of volatile aromatic compounds (61). Varieties like CSV 17 and AKJ 1 are used in porridges, malted drinks, popped snacks and fermented foods (9). Aroma compounds such as vanillin and maltol derivatives contribute to their unique sensory profile, while also offering antioxidant and antimicrobial properties (61). These varieties command premium prices in local markets, benefiting smallholder farmers engaged in specialty crop value chains (61).

Quality protein sorghum (QPS)

QPS varieties have elevated lysine and tryptophan levels, overcoming the amino acid deficiencies of traditional sorghum (62). Genotypes such as PYPS 1, PYPS 2 and PYPS 4 deliver 40 %-60 % more lysine without yield penalties, enhancing their utility in human diets and livestock feeds. In feed industries, QPS reduces reliance on costly protein supplements like soybean meal, improving economic efficiency (9, 62). Marker-assisted selection and opaque-2-based breeding approaches are being used to accelerate QPS development, similar to quality protein maize (QPM), supporting protein-energy malnutrition alleviation in vulnerable regions (61, 62).

Different sorghum types have been developed to suit diverse agro-ecological conditions and end-use requirements. Sorghum varieties have been developed to meet distinct needs such as grain, forage, bioenergy and nutrition. Fig. 3 highlights representative varieties and their primary applications. Each type is characterized by unique traits that determine its suitability for food, feed, fuel or specialty products. The key features, uses and representative varieties of major sorghum types are summarized in Table 3.

Sorghum improvement for diverse applications

The improvement of sorghum (*S. bicolor*) plays a crucial role in enhancing its utility as a climate-resilient crop for food, feed, fodder and industrial applications (1, 38). As global demand grows for sustainable cereals that perform well under challenging environments, strategic breeding and biotechnological innovations are essential to unlock sorghum's full potential, particularly in coping with drought, heat stress and salinity the most pressing abiotic

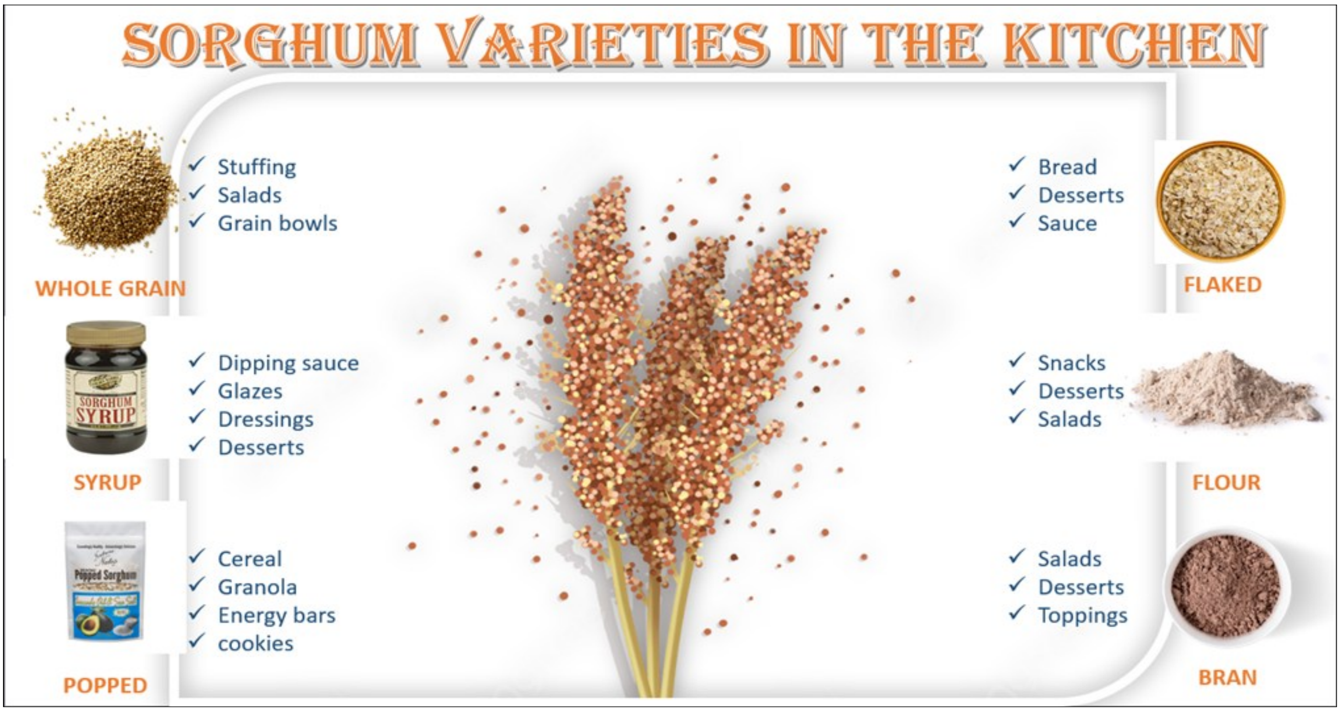

Fig. 3. Sorghum varieties used for various purposes.

Table 3. Types of sorghum: key traits, uses and example varieties

Type	Key traits	Major uses	Example varieties	Reference
Grain	High yield, low tannin	Food, feed, ethanol	CSV 17, PVK 801	(29-31)
Forage	Biomass yield, digestibility	Fodder, silage, biogas	COFS 29, BMR hybrids	(32, 34)
Sweet	High brix, drought tolerance	Syrup, ethanol	CSV 19SS, SSV 84	(35)
Biomass	High cellulose, stem mass	Biofuel, bioplastic	FS-5, Silage King	(36,37)
Popping	Pop volume, expansion	Snacks	PPC-9, PPC-4	(38)
Vegetable	Tender grains, sweetness	Roasted / baby corn	SSV 84, IS 18551	(39, 40)
Biofortified	High Fe, Zn, β-carotene	Fortified foods	ICSB 52, PVK 801	(41, 42)
Quick cooking	Low gelatinization temp	Instant foods	Parbhani Moti, Phule Vasudha	(43)
Aromatic	Fragrance, colour	Specialty foods	CSV 17, AKJ 1	(44, 45)
QPS	High lysine, tryptophan	Human and animal nutrition	PYPS 1, PYPS 4	(46, 47)

stresses affecting its productivity. (5, 38). Sorghum improvement efforts have historically focused on yield and stress tolerance; however, recent advancements have expanded to include biofortification, industrial suitability and biomass enhancement to meet the growing challenges of food security, renewable energy needs and climate change adaptation (42, 46, 56).

Conventional breeding approaches have long been utilised in sorghum improvement through selection, hybridisation and recurrent breeding to enhance yield, grain quality and stress tolerance (37, 38). Key targets include:

- Yield enhancement by improving panicle architecture, grain number and thousand-kernel weight (TKW) (29-31);
- Development of drought and heat-tolerant varieties by selecting for stay-green traits, deeper rooting and efficient transpiration regulation (33, 35); and
- Incorporation of resistance against major pests and diseases such as shoot fly, stem borer, midge, grain mould and anthracnose (40).

Forage and dual-purpose varieties are bred for higher digestibility and reduced lignin content to improve fodder quality, while early-maturing varieties are developed to suit diverse agro-ecological regions (37, 41). Institutions like ICRISAT, TNAU and Texas A&M University have released improved cultivars such as CSV 17, PVK 801 and BMR hybrids targeting these traits (45, 46).

Key QTLs and molecular markers have been identified in sorghum for traits such as drought tolerance, grain yield, biomass, sugar content and lignin reduction, supporting targeted improvement through marker-assisted selection (MAS), genomic selection (GS) and genome editing (Table 4).

Molecular breeding and MAS have accelerated sorghum improvement by enabling precise introgression of desirable traits (34, 44). Notable advancements include QTL mapping for traits such as drought tolerance (Stg1–Stg4 stay-green loci), plant height, biomass yield, sugar content and grain quality (33, 34, 42). MAS using SSR and SNP markers linked to these traits has improved selection efficiency and reduced breeding cycle duration, while emerging GS approaches leverage genome-wide marker data to predict breeding values, enabling rapid genetic gains for complex traits such as biomass yield and multi-trait improvement (44).

Biotechnological interventions further expand sorghum improvement, particularly for traits difficult to achieve through conventional methods (42). Genetic engineering has introduced genes conferring drought tolerance, insect resistance (e.g. Bt genes) and biofortification traits such as enhanced provitamin A, iron and zinc content (62). Genome editing using CRISPR/Cas9 has enabled precise editing of lignin biosynthesis genes such as *bmr6* and *bmr12* to reduce lignin content, thereby improving forage digestibility and biofuel conversion efficiency (41, 63). Transgenic biofortification approaches aim to increase lysine and tryptophan levels in sorghum to address protein-energy malnutrition, particularly in Sub-Saharan Africa (64). These advances are complemented by tissue culture techniques for *in vitro* regeneration, somaclonal variation exploitation and rapid multiplication of elite genotypes (65).

Despite significant progress, challenges remain in integrating high productivity with nutritional quality, industrial traits and climate resilience (38, 42). Future breeding priorities include:

- Pyramiding multiple stress tolerance traits with high yield potential;
- Developing varieties with tailored starch, sugar and lignin compositions for biofuel, brewing and biodegradable industries (47, 49, 56);
- Expanding genomic resources and bioinformatics tools for gene discovery and functional validation (44); and
- Strengthening participatory breeding to align varietal development with farmer preferences and market needs (38).

Furthermore, enhancing value chain development, market integration and supportive policies is critical to realise the full industrial and agricultural potential of improved sorghum varieties (5, 46). Continued integration of conventional breeding, molecular tools and biotechnological innovations is essential to harness sorghum's role as a climate-smart, nutritionally rich and industrially

Table 4. QTLs and genetic markers identified for sorghum improvement

Trait	QTL/Marker	Breeding strategy	Outcome	Reference
Drought tolerance	Stg1-Stg4	MAS	Stay-green, improved yield under stress	(34)
Grain weight	qGW1, qGW2	QTL mapping	Enhanced grain yield	(34)
Biomass yield	qBM	GS	High biomass for bioenergy	(44)
Sugar content	qBrix	MAS	Improved sweet sorghum	(42)
Lignin content	bmr6, bmr12	CRISPR/MAS	Better digestibility, biofuel conversion	(41)

valuable crop contributing to global food security, renewable energy and sustainable development (38, 42, 46).

Complementary breeding approaches from conventional methods to advanced biotechnologies are applied to enhance yield, stress tolerance, nutritional quality and forage value, aligning with diverse production needs (Table 5).

Recent global initiatives and projects in sorghum

Recent years have witnessed a remarkable rise in global initiatives focused on unlocking the full potential of sorghum for nutrition, health and industrial applications (46). One of the most impactful efforts is led by HarvestPlus, which has spearheaded biofortification projects across Africa and South Asia (66). In partnership with organizations like ICRISAT, HarvestPlus has developed and released biofortified sorghum varieties such as ICSR 14001, featuring up to 60 % higher iron and 40 % higher zinc content compared to conventional varieties. (67, 68). These varieties are now being introduced in countries including India, Saudi Arabia and Sudan, directly addressing micronutrient deficiencies in vulnerable populations (69). HarvestPlus also collaborates with the World Food Programme (WFP) and AGRA to incorporate biofortified sorghum into school feeding and institutional procurement programs, thereby improving nutrition and creating new market opportunities for smallholder farmers (70).

Another prominent initiative is ICRISAT's Smart Food program, which promotes sorghum as a "smart" choice for consumers, farmers and the environment (46). The Smart Food initiative raises global awareness about the nutritional, environmental and economic advantages of sorghum, while working to diversify both diets and farming systems (46). By connecting research, policy and market development, this program is helping to establish sorghum as a cornerstone of sustainable food systems in Africa, Asia and beyond (46).

In the realm of industrial use, the United States Department of Agriculture (USDA) and the Government of India have launched ethanol blending programs which are driving up demand for sorghum as a biofuel feedstock (10, 47). These policies are expanding market opportunities for sorghum growers and supporting the shift towards more sustainable, climate-friendly energy sources (47, 71). As a result, sorghum is increasingly recognized not just as a staple food and feed crop, but also as a key resource for green industry and climate-resilient agriculture (46, 47).

Together, these initiatives highlight the growing global recognition of sorghum's value and the importance of collaborative action to maximize its contributions to nutrition, economic growth and sustainability (46, 72).

Future Prospects

While sorghum research has come a long way, there are still important challenges and exciting opportunities ahead to unlock its full potential for food security, climate resilience and sustainable industry (38, 42). Moving forward, breeding programs should aim to combine multiple stress-tolerance traits like drought, heat and salinity resistance so that new sorghum varieties can thrive in the face of climate change (33, 35, 38). Achieving this will require stacking key genes and QTLs using advanced tools like marker-assisted and genomic selection (34, 44).

There is also a huge, largely untapped opportunity to develop sorghum varieties specifically for industrial uses - including bioethanol, biodegradable plastics and health-promoting bioactive compounds (47, 56). Future research should focus on boosting traits such as high stem sugar, optimal lignocellulosic structure and lower lignin content to make sorghum even more efficient for biofuel production (41, 56). Cutting-edge genome editing tools like CRISPR/Cas9 could speed up the improvement of traits related to nutrition, digestibility and industrial processing, though regulatory hurdles still need to be addressed before these advances can reach the market (41).

On the nutrition front, expanding the use of biofortified sorghum rich in iron, zinc and provitamin A is crucial to fight hidden hunger, especially in vulnerable communities. However, for these improved varieties to be widely adopted, they must also deliver stable yields, meet farmers' needs and be supported by strong market incentives (38, 46).

Strengthening the entire sorghum value chain is equally important. This means creating supportive policies, building better links between farmers and markets and investing in processing infrastructure (46, 47). Public-private partnerships can play a key role in growing sorghum-based industries, especially in areas like bioenergy, animal feed and health foods (47).

Ultimately, the future of sorghum will depend on interdisciplinary collaboration bringing together genetics, agronomy, food science and economics. Such teamwork will be essential to position sorghum as a strategic crop for sustainable agriculture and innovative industry in a changing climate.

Conclusion

Sorghum is a versatile, sustainable crop offering significant agricultural, industrial and environmental benefits. Its high biomass yield, drought resilience and ethanol efficiency support food security and renewable energy. Lignocellulosic traits enable biodegradable material production, reducing petrochemical reliance. Breeding and genomics have improved yield, disease resistance and digestibility. However, climate stress, pests and market barriers remain key challenges. Future initiatives should focus on enhancing crop resilience, optimizing biofuel production, leveraging biotechnology and improving nutritional quality. Strategic investments and collaboration can unlock sorghum's full potential for global sustainability and climate-smart agriculture,

Table 5. Sorghum breeding approaches and objectives

Approach	Objective	Application	Reference
Conventional breeding	Yield, stress tolerance, maturity	Grain, forage, sweet sorghum	(29-31, 37)
Marker-assisted selection	Drought, grain traits	Stay-green, yield	(34)
Genomic selection	Complex traits	Biomass yield, multi-trait improvement	(44)
Genetic engineering	Biofortification, insect resistance	Nutritional security, pest resistance	(42, 78)
Genome editing	Lignin reduction	Forage quality, biofuel efficiency	(41)

positioning it as a keystone crop in future food systems aligned with the SDGs and global climate-resilience frameworks.

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Authors' contributions

VR was responsible for conceptualization, visualization, writing the original draft, review and editing. MK as the corresponding author, led the manuscript writing, editing, conceptualization and supervision. DK, MD and PM contributed to the discussion. All authors read and approved the final manuscript.

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