Review article

Harnessing Sweet Sorghum for Renewable Energy and Bioproducts – A Review

Abstract:

Sweet sorghum is a versatile crop valued for its grain, fodder, and high-sugar stalks used in syrup and bioethanol production. Its ability to grow well in dry and low-input conditions makes it suitable for cultivation in semi-arid and rain-fed regions. Understanding the processes involved in sugar accumulation and bioethanol production, along with the plant traits that influence these processes, is essential for further improvement. Studying the relationships among traits such as Brix, juice yield, biomass, plant height, and moisture helps identify the key factors that determine sugar and ethanol output. Knowledge of these traits, together with suitable breeding strategies, supports the development of improved varieties with higher efficiency and better adaptability. Overall, integrating trait evaluation with breeding approaches can accelerate the advancement and wider use of sweet sorghum in food, fodder, and renewable energy systems.

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Key words: Sweet sorghum, bioethanol, Brix, juice yield, biomass

Introduction:

The rapid increase in global population and economic activity has resulted in a rise in energy demand. To meet these needs, fossil fuels have been exploited at greater levels, leading to severe environmental and climatic consequences. The extensive burning of coal, oil, and natural gas is the primary driver of carbon dioxide (CO_2) emissions, contributing significantly to global warming and declining air quality. According to **Wolf *et al.*, 2025** the United Nations Secretary-General António Guterres, has warned that continued dependence on fossil fuels threatens human survival, highlighting the urgent need for renewable energy expansion.Fossil fuel dependence is associated not only with increased greenhouse gas emissions but also with multiple social and public-health challenges. Air pollution, climate change, heat stress, and reduced quality of life are among the major negative impacts documented worldwide (**Martins *et al.*, 2018; Solarin, 2020; Gani, 2021**).

India is a striking example of this trend. National CO_2 emissions have increased dramatically - from 25.87 million tonnes in 2000 to 231.62 million tonnes in 2023. With energy demands projected to rise further, India is expected to surpass the United States and become the second-largest global emitter by 2035. At present, India ranks third in global greenhouse gas emissions, releasing 4.41 billion tonnes of CO_2-equivalent in 2023 alone (**India: CO2 Country Profile - Our World in Data**, **GHG emissions in India - Statistics & Facts | Statista**, **How India's greenhouse gas emissions stack up globally**, **Greenhouse Gas Emissions by Country 2025**).

These alarming trends highlight the urgent necessity to shift from fossil fuels to renewable alternatives. Among these, biofuels particularly those derived from non-food biomass

- represent a promising and sustainable option. Biofuels are renewable energy sources derived from biological materials such as plants, animals, microorganisms, and organic wastes. A wide spectrum of liquid and gaseous biofuels including ethanol, biodiesel, methanol, methane, and bio-oilcan be produced from biomass-based feed stocks **(Ambaye *et al.*, 2021; Malik *et al.*, 2024).** Biomass contains organic components that can be converted into solid, liquid, or gaseous fuels and thus serves as a sustainable alternative to fossil energy (**Datta *et al.*, 2019; Mahmood *et al.,* 2023; El-Araby, 2024**). Biofuels are classified into four generations based on feedstock and technology. First-generation biofuels depend on edible crops (like wheat, corn, potatoes, sugarcane, beet, sweet sorghum etc.) and therefore compete with food resources (**Sadaqat et al., 2025; Hilário et al., 2024**). Second-generation biofuels use non-edible lignocellulosic biomass, offering a carbon-neutral alternative but still facing technological and economic limitations (**Yupanqui et al., 2024; Makkawi et al., 2023**). Third- and fourth-generation biofuels, derived from algae and genetically engineered microorganisms respectively, provide higher productivity and advanced carbon-capture potential, though high processing energy and complexity remain challenges (**Osman et al., 2021; Cavilleus et al., 2023; Aron et al., 2020**).

Sweet sorghum is primarily classified as a first-generation (1G) bioethanol feedstock due to its fermentable sugars in the stalk juice, although its lignocellulosic bagasse can also serve as a second-generation (2G) substrate. It is a tall, juicy, high-biomass type of sorghum and represents a natural variant of grain sorghum with significantly higher sugar content (**Lyu et al., 2019**). Its rapid growth, adaptability, and high reducing sugar levels often surpassing those of sugarcane juice preventing crystallization and enable near-complete fermentation efficiency in bioethanol production (**Mathur et al., 2017, Xiao *et al.,* 2021)** ven these advantages, sweet sorghum has gained considerable attention as a sustainable and resource-efficient biofuel feedstock and sugar rich cereal crop**.**

Agronomic Advantages

Sweet sorghum Known as a "smart" crop and also known as the "camel among crops" by many scientists and farmers (**Mokariya and malam 2020).** It is a highly productive C4 cereal in the grass family, known for its high photosynthetic efficiency and strong ability to grow in acidic and dry lands. Sorghum with stem sugar content greater than 8° Brix is classified as sweet sorghum (**Lestari et al., 2020; Endang et al., 2019; Ghallab & Helmy, 2023**). It can reach up to 20 feet and produces a high biomass yield, with stems that are wider and fleshier than those of grain sorghum. Its high biomass production and stem sugar accumulation further highlight its strong bioenergetic potential (**López-Sandin et al., 2021; Punia & Kumar, 2025).**Sweet sorghum, grows best at temperatures above 12°C and is well adapted to drought, salinity, and waterlogging, with high water use efficiency (**Almodares et al., 2009; Rathnavathi et al., 2011; kumar et al 2024**). Its tolerance to stress and low-input requirements make it a promising biofuel crop, offering opportunities for smallholder farmers in rural areas (**Rao et al 2013; Mengistu et al., 2016**)

From the 1970s to the 1980s, sweet sorghum was widely studied in the USA as a raw material for ethanol, as it can be harvested within 4–6 months even in temperate regions (**Tsuchihashi & Goto, 2004**). Compared with traditional bioenergy crops like corn, sugarcane, and sugar beet, sweet sorghum requires substantially less water and lower management inputs, can be harvested during the off-season of sugarcane, and can be processed using the same industrial infrastructure. These advantages along with its high biomass yield, early maturity, and ability to extend the milling period, increases its value as an efficient biofuel crop (**Umar et al., 2025; Silva et al., 2018; Chaitrashree et al., 2024**). Its stem sap, rich in fermentable sugars (53–85% sucrose, 9–33% glucose, 6–21% fructose), can be directly converted into bioethanol (**Chaithrashree et al., 2024**).

Nutritional status:

Sweet sorghum is not only a rich source of fermentable sugars but also contains diverse phenolic compounds and flavonoids that contribute to its functional properties. Its syrup is dominated by phenolic acids such as ellagic, protocatechuic, sinapic, and vanillic acids, along with lower amounts of chlorogenic and gallic acids, while flavonoids like catechin, naringin, and apigenin are present in smaller quantities (**Kurella et al., 2022; Yara et al., 2024**). Nutritionally, sweet sorghum contains 8.36% crude protein, 3.21% fat, 27.13% carbohydrates, and 3.21% fiber, with high reducing (3.61%) and total sugars (4.24%) that impart its characteristic sweetness (**Samarth et al., 2018**). Its mineral composition is notable, including calcium, magnesium, potassium, and iron, while the juice also provides starch, sucrose, glucose, fructose, amino acids, ascorbic acid, carotene, and other essential minerals such as zinc, phosphorus, and sodium **(Chibrikov et al., 2023, Vinutha et al 2014**). Together, these attributes make sweet sorghum a promising crop both for bioethanol production and nutritional applications

Table 1-Sugarcane Vs Sweetsorghum Vs Maize

S.No	Character	Sugarcane	Sweet Sorghum	Maize
1.	Crop duration	10–14 months	4–5 months	3–4 months
2.	Water requirement	1100–1500 mm	~600 mm	~238 mm
3.	Inputs	High	Low	High
4.	Propagation	Setts	Seed	Seed
5.	Yield (India)	83.35 t/ha (cane)	40–60 t/ha (fresh stalk) (1.08 t/ha - grain)	3.54 t/ha (grain)
6.	Sugars (type)	Very high sucrose	High reducing sugars + sucrose	Lowest total sugars
7.	Total sugar (%)	12–16%	15–21%	1–3%
8.	By-products	Bagasse, molasses	Bagasse, grain	Stover, cobs
9.	Total ethanol production (lt/ha)	8925	3160	3216

Sources: Data compiled from Vinutha et al. (2014); Roja et al. (2020); Dingre et al. (2020); Ramos et al. (2012); Makur et al. (2019); Ingle et al. (2024); Kumar et al 2024.

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Sweet sorghum stands out among biofuel crops due to its shorter crop duration (4–5 months), lower input requirement, and ability to grow under water-limited conditions and all seasons while being resistant to biotic and abiotic stress, compared with sugarcane and maize.

While sugarcane has a longer duration (10–14 months) and requires high water (1100–1500 mm) and inputs, sweet sorghum requires approximately 1200 mm and thrives even on marginal lands. Its stalk sugar concentration (15–21% Brix), dominated by fermentable reducing sugars and sucrose, often exceeds that of sugarcane (12–16% Brix), and its biomass yield ranges between 40–60 t/ha. Maize, although a major cereal, contains the lowest soluble sugars (1–3%) and is therefore not a viable feedstock for direct ethanol production.

Global status of sweet sorghum:

Global sweet sorghum markets are growing steadily, increasing from US $5.70 billion in 2024 to a projected US $7.80 billion by 2030 (CAGR ~5.5%) **(Grand View Research, 2024)**. The sweet sorghum-based ethanol sector shows similar expansion, with the Asia-Pacific market valued at US $0.73 billion in 2024 and expected to grow at ~7% annually **(Asia Pacific Sweet Sorghum Ethanol Industry Report, 2025)**, while global sweet sorghum ethanol revenues are forecast to rise from US $3.55 billion in 2025 to US $5.12 billion by 2033 (CAGR 4.69%) **(Global Sweet Sorghum Ethanol Industry Trends Report, 2025–2033)**. Future projections suggest that sweet sorghum could expand into 25 million ha of new cultivation area across Asia, Africa, and South America, strengthening farmer participation in biofuel markets **(CGIAR, 2024)**. In the U.S., favorable renewable fuel policies have supported a 35% increase in sorghum-based ethanol production since 2021, driven by low carbon intensity scores **(Sawal, 2025)**. Country-wise, India is expected to register the highest CAGR from 2025 to 2030, reflecting its growing adoption of sweet sorghum for bioethanol production **(Grand View Research, 2024).**

Table 2-Different genotypes of sweet sorghum majorly cultivated

Genotypes	**Reference**
SSV 84, CSV19 SS, CSH22 SS, CSV24 SS, ICSV 93046, ICSV 25274, ICSV 700, ICSSH 39, ICSSH 58, SPH 1711, SPH 1669, SPH 1712, SPH 1713, SPH 1670,	Rao et al
Suwan sweet1, Suwan sweet extra, Cowley, KKU40, SSV 84, Suwan sweet 2	Bunphan et al 2025
ICSV 25316, ICSV 25311, SSV 74, ICSV 25300	Pinnamaneni et al 2022
Rostovsky, Zubr, Dela-varieta, Simon, Kazakhstanskaya20	Baiseitova et al 2021

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Products of Sweet sorghum

1. **Sugar production**

Sugar accumulation in sweet sorghum is influenced by variety, temperature, water availability, salinity, and tolerance to waterlogging and genetic improvement for sugar yield in sweet sorghum has received less attention compared to sugarcane. Sweet sorghum juice typically contains 16–18% fermentable sugars, mainly sucrose, glucose, and fructose, which is comparable or superior to sugarcane juice (12–17.6%), sugar beet juice (16%), and much higher than watermelon juice (7–10%) **(Jia et al., 2013; Ratnavathi et al 2011; Appiah-Nkansah et al., 2015)**. Based on the predominant type of sugar stored in the stalk, sweet sorghum is classified into saccharin-type, rich in sucrose suitable for crystal sugar production, and syrup-type, which contains more glucose and is used for syrup extraction (**Almodares et al., 2009; Mukabane et al., 2014; Mengitsu et al 2016; Habtegiorgis et al., 2025**).

For juice extraction, stalks are commonly processed using two-roller presses, which provide around 25–30% extraction relative to stalk weight. More complete extraction can be achieved using three-roller presses, which increase juice recovery to 42–47% (**Husiatynska et al., 2021**). Many studies, including **Rao et al. (2013**), extracted sweet sorghum juice using power-operated three-roller sugarcane mills without imbibition water. Sweet sorghum stalks can also be harvested and delivered to mills before the sugarcane crushing season, making it a suitable complementary feedstock (**Mathias et al., 2023**). After extraction, suspended solids are removed by wire and fine-mesh filtration, and the clear juice is evaporated in stainless-steel pans where heat coagulates non-sugars, which are skimmed off to improve clarity; the resulting syrup is cooled, bottled, and measured for °Brix (**Yara et al., 2024**). At industrial scale, purification begins with liming and carbonation, where lime milk and CO_2 precipitate impurities, producing thin juice (~15% sugars) that is then concentrated in multiple-effect evaporators to thick juice containing ~70% sugars (**Mukabane et al., 2014).**This extracted sugar from sweet sorghum stalks can also be processed and concentrated to produce sweet sorghum syrup, which is used as a natural sweetener and as a raw material for food products.

With the extracted and clarified sweet sorghum juice, the following major Product is Bioethanol.

2. Bioethanol production

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Sweet sorghum is considered a dual-purpose bioenergy crop because its sugar-rich juice is used for first-generation (1G) ethanol, while its fiber-rich bagasse serves as a feedstock for second-generation (2G) lignocellulosic ethanol (**Khalil et al., 2015; Nazli et al., 2024**). The juice extracted from the stalks contains high levels of fermentable carbohydrates (mainly sucrose and glucose), making it ideal for direct fermentation, and microorganisms such as *Saccharomyces cerevisiae* and *Zymomonasmobilis* can efficiently convert these sugars into ethanol (**Khalil et al., 2015; Walker & Stewart, 2016; Kasegn et al., 2023**). Theoretically, yeast converts 1 g of glucose into 0.511 g of ethanol, highlighting the high efficiency of sugar-based substrates (**Klasson & Boone, 2021; Oktem et al., 2024**). Under standard cultivation and processing conditions, sweet sorghum can produce up to 1.32 t ha^{-1} of total sugar and ~768 L ha^{-1} of ethanol, demonstrating its strong potential as a 1G feedstock (**Oktem et al., 2024**).In the 2G pathway, sweet sorghum bagasse—a lignocellulosic residue from juice extraction—serves as a valuable raw material for producing ethanol, biogas, hydrogen, paper, and other bio-based products (**Nazli et al., 2024**).While high-sugar juices are ideal for very-high-gravity (VHG) fermentation, lignocellulosic residues generally contain lower sugar concentrations (40–120 g/L), making them less suited for VHG systems and introducing challenges typical of 2G ethanol substrates (**Thatiyamanee et al., 2025**).

Pretreatments:
To efficiently convert bagasse into fermentable sugars, pretreatment is essential to disrupt lignocellulosic structure, enhance enzyme accessibility, and improve downstream

hydrolysis.Recent research explores a range of chemical, physical, and biological pretreatment methods to enhance enzymatic hydrolysis and ethanol production.

Table 3: Different Pre treatment methods of Sweet Sorghum

Pretreatment Type	**Findings**	**References**
Alkaline	NaOH-based treatments (with ensiling or steam explosion) effectively remove lignin/hemicellulose, improve cellulose accessibility, and give high ethanol yields. Best results with 10% NaOH for 30 min (66.88 g/L ethanol) and ensiling + NaOH improving saccharification.	Zhao et al. 2024; Sudiyani et al. 2016
Acid	Mild dilute acid (0.90% H_2SO_4) enhances glucose release and yields ~23 g/L ethanol, while severe acid (3% H_2SO_4 at 134°C) reduces ethanol due to sugar degradation. Acid pretreatment is useful only at low severity.	Buruiana etal. 2020; Kreetachat et al. 2025
Physical	Milling and steam explosion mainly increase surface area and disrupt structure. Alone they don't remove lignin, but greatly enhance chemical/enzymatic pretreatment efficiency; steam explosion with alkali improves cellulose conversion.	Tu & Hallett 2019; Alqahtani 2024; Zhu et al. 2023;
Hydro thermal	High-temperature water solubilizes hemicellulose and releases sugars with fewer inhibitors. Increased severity increases sugar release but raises energy use; hydrothermal PSSF produced 22.17 g/L ethanol.	Sandin et al. 2022

In summary, which pretreatment method works best depends on how tough the biomass is, the energy needed, and its specific traits. Alkaline and hydrothermal methods usually yield more sugars and ethanol, but mild acid treatments and physical methods can also be successful if done right. Choosing the right pretreatment is key to getting the most bioethanol from sweet sorghum.

Distillation and Ethanol Recovery:

Following fermentation, distillation is the final step in bioethanol production and determines the purity and overall energy efficiency of the process. Studies have evaluated conventional, semi-centralized, membrane-based, and alkali-assisted distillation systems for sweet sorghum-derived ethanol

Table 4: Different Distillation and Ethanol Recovery methods of Sweet Sorghum

Method	Process	Outcome	References
Alkali-assisted distillation + enzymatic hydrolysis	Fermented bagasse mixed with concentrated alkali and distilled; lignin-rich black liquor removed; residual solids enzymatically hydrolyzed	Disrupts bagasse structure; improves hydrolysis; enables sequential ethanol recovery	Li et al., 2013
Semi-centralized distillation + molecular sieve dehydration	Fermented ethanol transported to facility; distilled to 95 wt.% and dehydrated to 99.7 wt.%	Efficient large-scale ethanol purity; steam or bagasse used as energy source	Olukoya et al., 2015
Conventional distillation (95–99.6% ethanol)	Distillation column concentrates ethanol to 95% v/v; further concentration to 99.6% v/v	Produces fuel-grade anhydrous ethanol	Sasaki et al., 2014; Ratnavathi et al., 2011
Solar/vacuum distillation	Vacuum or solar-driven units distill ethanol–water mixtures (7–70% ethanol)	Achieves 40–60% ethanol; high energy efficiency; positive energy balance (3.94)	Rajvanshi et al., 1984
OPTS (Integrated ASSF + CSSD + VP) (OPTS – One-Pot Total System; ASSF – Advanced Simultaneous Saccharification and Fermentation; CSSD – Continuous Solid-State Distillation; VP – Vapor Permeation)	Combines fermentation, solid-state distillation, and vapor separation in one integrated system	Only one phase change, low energy consumption, higher efficiency, reduced energy loss, and easily scalable with improved VP membranes	Li et al., 2021

This comparative table highlights how different distillation and ethanol recovery systems vary in efficiency, cost, and scalability. Thus, with optimized pretreatment and energy-efficient distillation, sweet sorghum offers are liable and scalable pathway for producing both first and second generation bioethanol

Breeding strategies for sweet sorghum for ethanol production:

As the efficiency of bioethanol production is determined not only by processing technologies but also by the inherent biological potential of the crop, improving the genetics of sweet sorghum becomes essential. Its improvement has mainly relied on conventional breeding methods, particularly selection, hybridization, and pedigree breeding. Early breeding focused on selecting local landraces for high juice content, high Brix%, tall stalks, and delayed flowering. Later, planned crosses were made between sweet and grain sorghum types to combine high sugar accumulation with better agronomic traits such as lodging resistance and pest tolerance. Pedigree selection is widely used to identify superior recombinant lines across generations, especially for traits like Brix%, juice yield, and biomass. For hybrid development, cytoplasmic male sterility (CMS-based A/B/R line breeding) is used, enabling high heterosis for traits contributing to bioethanol production. These conventional approaches have resulted in the release of several productive varieties and hybrids such as SSV 84, CSV 19SS, CSH 22SS, and ICSV series lines.

Table 5: Some Important varieties Brix(%) value

S.No	Variety / Hybrid	Breeding Method	Brix (%)
1	CSH 22S	ICSA 38 × SSV 84	17–18
2	SSV 84	Released by AICRP (NRCS Hyderabad)	17–18
3	CSV 19SS	RSSV 2 × SPV 462	17–18
4	SSV 74	Released by UAS Dharwad	17.6
5	ICSV 93046	Pedigree selection from ICSV 700 × ICSV 708	16–17
6	ICSV 25274	Pedigree selection from DSV 4 × SSV 84	18
7	ICSV 700	Developed at ICRISAT	17–19
8	ICSSH 39	ICSA 702 × SSV 74	15
9	ICSSH 58	ICSA 731 × ICSV 93046	16
10	CSV 24SS	Candidate for central release	—

Important traits and genetic factors influencing sweet sorghum for sugar and bioethanol production:

Sweet sorghum displays strong heterosis for key traits linked to ethanol production, including Brix, biomass, plant height, juice yield, and total soluble solids, making hybrid breeding an effective strategy for improving biofuel traits (**El-Abed et al., 2021; Bandara et al., 2019**). Ethanol yield is influenced by many interconnected agro-industrial traits, and tons of Brix per hectare (TBH) has been identified as a reliable indirect selection criterion because of its strong positive association with ethanol output (**Leite et al., 2017; Botelho et al., 2021; Lombardi et al., 2015**).Juice yield and soluble solids depend strongly on stalk moisture, but moisture content is a quantitative trait and does not correspond well with visual traits like stalk pithiness. High-Brix regions such as the major QTL on chromosome 3 often co-localize with biomass-related loci, meaning that selecting for high Brix may unintentionally reduce biomass. Many compositional traits are genetically linked to agronomic traits, requiring careful simultaneous evaluation during selection **(Felderhoff et al., 2011**).

Environment also alters trait relationships. Under normal conditions, a major region on chromosome 9 shows negative association between stem sugar and grain yield, whereas under stress (midge pressure or excess rain), a QTL on chromosome 6 becomes responsible for this sugar - grain yield negative association. This indicates that stress can intensify negative correlations between sugar and grain traits (**Murray et al., 2008**). Additionally, sucrose and soluble solids peak at grain maturity, allowing dual harvesting of grain and stalks for increased farmer revenue **(Abedugba et al., 2023**).

Most sugar-related traits are controlled primarily by additive genes, with several QTL showing pleiotropic or co-localized effects. A key region at 14 cM on SBI-06 increases multiple sugar traits, emphasizing the usefulness of stacking favourable alleles. Both major and minor QTL, epistatic interactions, and QTL × environment effects must be considered for effective improvement (**Shiringani et al., 2010**). Multi-environment studies have further identified QTL for height, biomass, stem moisture, stem diameter, Brix, and flowering across chromosomes 1, 6, 7, and 9, with several QTNs explaining 5–14% of variation (**Teingtham et al., 2022; Umar et al., 2025; Guden et al., 2023**). Mutation breeding has also generated lines with improved stem diameter, plant height, juice volume, and biomass, although stability varies across environments. Some mutants perform exceptionally well in specific conditions and may serve as promising cultivars for targeted cultivation (**Syahruddin et al., 2021**).

CONCLUSION:

Sweet sorghum is becoming an increasingly valuable crop because it can supply grain for food, fodder for livestock, and fermentable sugars for syrup and bioethanol. Its ability to grow well in dry and rain-fed areas, with lower water and fertilizer needs compared to other sugar crops, makes it especially important for semi-arid agriculture. Many studies have shown that major traits such as Brix, juice yield, biomass, stem moisture, and plant height are controlled by both genetic factors and environmental conditions. Thus careful evaluation of these traits across different locations and seasons required to identify stable, high-performing genotypes.

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However, sweet sorghum faces several constraints that slow down its wider adoption.The Sugar content and juice volume may vary with environmental conditions like temperature, rainfall, and soil moisture, leading to inconsistent performance. The crop is also affected by key pests such as shoot fly, stemborer, and sometimes aphids, which can reduce plant Vigor and juice yield. Another challenge is that the sugar percent decline rapidly after the harvest, that means that the stalks need to be processed quickly, which is difficult in areas lacking nearby crushing or fermentation facilities. Limited availability of improved hybrids, weak market support, and competition with crops like sugarcane and grain sorghum further limit its commercial expansion in many regions.But on the positive side, breeding programs have also made good progress. Hybrid breeding is effective because many sugar-related traits show strong heterosis, allowing development of varieties with better Brix, higher biomass, and improved juice extraction. Works done on QTLs has helped to identify important genome regions responsible for sugar traits, moisture, height, and flowering time. These studies support more accurate and faster selection in breeding programs. Mutation breeding has also yielded promising lines with thicker stems, more juice, and better biomass in specific environments. These advancements highlight sweet sorghum's robust genetic potential for further improvement.

Overall, sweet sorghum is a promising multi-purpose crop that can support food security, livestock feeding, and renewable energy production. With continued research in breeding, better management, improved processing infrastructure, and strong market linkages, sweet sorghum can play a major role in future sustainable farming systems.

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