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Optimization of Efficient Cultivation Models for Edible Sorghum

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Abstract This study reviews the optimization of efficient cultivation modes for edible sorghum, focusing on challenges such as climate change, resource constraints, and pest pressure. The studyexplores the agricultural ecological needs of sorghum, including its adaptability to climate and soil conditions, as well as its nutritional requirements; Analyzed the research progress on using advanced genetic tools to cultivate new sorghum varieties with strong stress resistance and good regional adaptability. A summary was conducted on key agronomic practices such as planting techniques, fertilization management, and irrigation strategies to improve yield and resource utilization efficiency. In addition, the studyalso introduces how integrated pest and disease management, soil and water resource protection, and the application of modern technologies such as precision agriculture and decision support systems can further improve the productivity of sorghum. The case study demonstrates the optimization mode of sustainable cultivation of sorghum, including farmer innovation that adapts to local conditions and environmentally friendly farming methods. At the same time, the studyanalyzes the main obstacles to implementing efficient models, such as resource scarcity, environmental pressure, and insufficient policy support. At the end of the review, suggestions were put forward to optimize cultivation strategies, promote genetic improvement, and promote planting patterns according to local conditions, providing a scientific basis for achieving sustainable sorghum production and ensuring global food security.
Keywords Sorghum cultivation optimization; Stress-resistant varieties; Precision agriculture; Sustainable farming practices; Agroecological adaptation

1 Introduction

Sorghum (*Sorghum bicolor* L.) is a vital cereal crop, ranking among the top five globally in terms of production and planting area. Its significance is particularly pronounced in regions facing severe abiotic stresses, such as drought and saline-alkali soils, due to its remarkable stress resistance (Zheng et al., 2023). Sorghum serves as a crucial food source for millions, especially in sub-Saharan Africa and South Asia, where it thrives under limited input conditions and adverse climate scenarios (Khalifa and Eltahir, 2023). This resilience makes sorghum an essential crop for ensuring food security in the face of climate change, offering a robust line of defense against food shortages (Khalifa and Eltahir, 2023).

Despite its resilience, sorghum cultivation faces significant challenges. Climate change poses a threat by potentially pushing the crop's growing conditions beyond its tolerance limits, which could jeopardize food security for millions (Khalifa and Eltahir, 2023). Additionally, while sorghum is adaptable, it is not immune to the impacts of global warming, which necessitates improved cultivation practices to sustain yields. The need for efficient management practices, such as the use of tolerant cultivars, improved irrigation, and better agronomic techniques, is critical to overcoming these challenges and boosting sorghum yields (Khalifa and Eltahir, 2023).

This study focuses on exploring and optimizing efficient cultivation methods for edible sorghum to enhance its stress resistance and yield. We conduct an in-depth analysis of the latest research achievements in sorghum agriculture, with a particular emphasis on cultivating multifunctional sorghum varieties that can adapt to environmental pressures and have high economic value through genetic engineering technology, the application of wild sorghum genetic resources, and the utilization of genomic resources. Our ultimate goal is to provide insights and guidelines on sustainable sorghum cultivation, aimed at addressing the challenges posed by climate change and promoting global food security.

2 Agroecological Requirements for Sorghum

2.1 Climate and soil preferences

Sorghum is well-suited to a variety of climates, particularly those characterized by drought and high temperatures, due to its inherent drought tolerance and lower water requirements compared to other cereal crops like corn (Tonitto and Ricker-Gilbert, 2016; Kothari et al., 2019). It thrives in semi-arid regions, such as the dry savanna of West Africa and the Texas High Plains, where efficient water management is crucial for sustainable production (MacCarthy et al., 2010; Amouzou et al., 2018). Sorghum can also adapt to different soil types, including sandy soils with low fertility, as seen in the Southern Guinea Savanna of Nigeria (Akinseye et al., 2023). The crop's ability to withstand both drought and waterlogging makes it a versatile option for diverse agro-ecological zones (Tonitto and Ricker-Gilbert, 2016).

2.2 Nutritional requirements

Sorghum's growth and yield are significantly influenced by nutrient management, particularly nitrogen (N) and phosphorus (P) (MacCarthy et al., 2010; Tonitto and Ricker-Gilbert, 2016). Efficient use of these nutrients is essential for optimizing yield and maintaining soil health. Studies have shown that sorghum can benefit from both organic and inorganic nutrient amendments, with yield improvements ranging from 43% to 98% depending on the management practice (Tonitto and Ricker-Gilbert, 2016). In semi-arid regions like Ghana, the application of mineral N fertilizers has been found to enhance both yield and water use efficiency, with optimal rates varying based on field management intensity (MacCarthy et al., 2010). Additionally, integrating organic matter into the soil can further improve nutrient use efficiency and crop productivity (MacCarthy et al., 2010).

2.3 Crop physiology and growth stages

Sorghum's growth is characterized by distinct physiological stages, each with specific environmental and management requirements. The crop's development is influenced by temperature and photoperiod, with growth stages including germination, vegetative growth, flowering, and grain filling (White et al., 2015). Sorghum's ability to maintain functional equilibrium between roots and shoots is crucial for its adaptation to varying environmental conditions (White et al., 2015). The crop's rooting depth, for instance, can be optimized to enhance water uptake and reduce irrigation needs, as demonstrated in studies on sweet sorghum in subtropical environments (López et al., 2017). Understanding these physiological traits is vital for developing efficient cultivation models that maximize yield and resource use efficiency.

3 Genetic Resources and Varietal Selection

3.1 Breeding for edible sorghum

Breeding efforts for edible sorghum have increasingly focused on utilizing advanced genetic tools to enhance crop resilience and productivity. Marker-assisted breeding has been pivotal in developing high-yielding, disease-resistant, and climate-resilient sorghum cultivars. This approach has significantly reduced the time required to introduce new varieties adapted to challenging environmental conditions (Baloch et al., 2023). Genomic selection has also been employed to predict phenotypic performance, expediting the development of new cultivars with improved traits such as drought tolerance (Charles et al., 2024). Additionally, exploring genetic diversity for traits like nitrogen use efficiency (NUE) has been crucial in developing sorghum genotypes that perform well under varying nitrogen regimes, thereby enhancing yield potential (Figure 1) (Bollam et al., 2021; Ostmeyer et al., 2022).

3.2 Stress-resilient varieties

Developing stress-resilient sorghum varieties is essential for ensuring food security in regions prone to abiotic stresses such as drought and high temperatures. Breeding programs have focused on traits like stay-green, root architecture, and transpiration efficiency to enhance drought tolerance (Prasad et al., 2021). The integration of genomic prediction models has facilitated the selection of sorghum varieties that can withstand both biotic and abiotic stresses, particularly in environments with unpredictable rainfall patterns (Charles et al., 2024). Moreover, the use of epigenetic variation has shown promise in increasing yield stability and resilience under stress conditions, offering a novel approach to breeding stress-resilient sorghum (Ketumile et al., 2022).

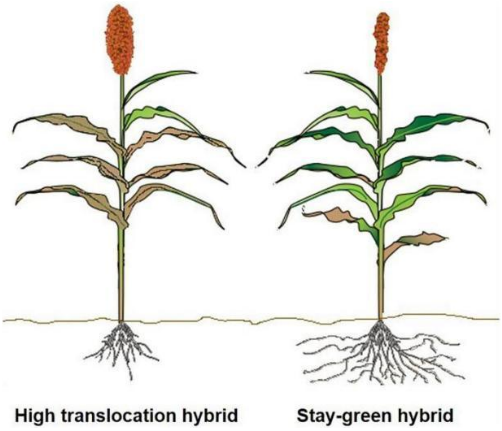

Figure 1 Illustration comparing sorghum hybrids with increased terminal senescence under favorable environmental conditions with greater N translocation from leaves to increase yield and grain quality (left) versus stay-green sorghum hybrids grown under resource-poor conditions (right). Sorghum hybrids with efficient translocation of N and increased senescence under less stressful environments would potentially not require an extensive root system (left) (Adopted from Ostmeyer et al., 2022)

3.3 Regional adaptation

Regional adaptation of sorghum varieties is critical for optimizing cultivation in diverse environmental conditions. In West Africa, for instance, breeding strategies have focused on developing varieties with traits such as photoperiod sensitivity and phosphorus efficiency to cope with climate variability (Haussmann et al., 2012). Multi-trait stability selection methods have been employed to ensure that sorghum genotypes maintain high yield and adaptability across different growing seasons and locations (Behera et al., 2024). Additionally, the selection of sorghum varieties specifically adapted to low-phosphorus environments has been shown to be more efficient than indirect selection, highlighting the importance of targeted breeding for regional adaptation (Leiser et al., 2012).

4 Agronomic Practices for High-Yielding Sorghum

4.1 Sowing techniques

Sowing techniques play a crucial role in optimizing sorghum yield, particularly in regions with varying climatic conditions. The timing of planting is essential to maximize yield, as demonstrated in a study using the APSIM crop model in Nigeria, which identified optimal planting windows for different sorghum cultivars across diverse agro-ecological zones. The study found that planting within these windows, which varied by region and cultivar, significantly increased yield potential (Akinseye et al., 2023). Additionally, a simulation analysis in Texas highlighted the importance of selecting appropriate planting dates and cultivar maturity to maximize yield under different irrigation strategies. Early or medium-maturing cultivars planted in early June were optimal for certain irrigation levels, while later-maturing cultivars performed better with different irrigation strategies (Baumhardt et al., 2007; Hong and Huang, 2024).

4.2 Fertilizer management

Effective fertilizer management is critical for enhancing sorghum yield. A study using response surface methodology optimized sorghum yield by varying the application of organic and inorganic fertilizers. The study found that a combination of nitrogen fertilizer, goat manure, and foliar fertilizer significantly increased yield, with nitrogen being the most impactful. Another study in a dryland wheat-sorghum-fallow rotation demonstrated that no-tillage combined with nitrogen application significantly improved sorghum yield and nitrogen use efficiency. The study recommended a nitrogen rate of up to 135 kg/ha for optimal results (Majrashi et al., 2022). Furthermore, research in Ghana showed that mineral nitrogen application at rates of 40 to 80 kg/ha was economically optimal, improving both yield and water use efficiency (MacCarthy et al., 2010).

4.3 Irrigation strategies

Irrigation strategies are vital for sorghum cultivation, especially in water-scarce regions. In the Texas High Plains, simulation models identified optimal irrigation strategies based on climate variability, suggesting that initial soil moisture and irrigation thresholds should be adjusted according to weather conditions to maximize yield and water use efficiency (Kothari et al., 2019). In the U.S. Central High Plains, the AquaCrop model identified efficient irrigation scheduling strategies, recommending a 10-day irrigation interval combined with pre-season irrigation to field capacity for optimal forage sorghum yield (Fazel et al., 2023). Additionally, a study in Iran compared drip and furrow irrigation methods, finding that drip irrigation, particularly under moderate water deficit conditions, improved both yield and water use efficiency (Ghalkhani et al., 2023). Another study in Heilongjiang Province, China, highlighted the importance of balancing irrigation and nitrogen rates to optimize growth and minimize soil nitrate accumulation, recommending a soil moisture limit of 70% field capacity and a nitrogen rate of 150 kg/ha (Ghalkhani et al., 2023).

5 Integrated Pest and Disease Management

5.1 Common pests and diseases

Sorghum is susceptible to a wide range of pests and diseases that can significantly impact its yield and quality. Key insect pests include the sorghum shoot fly (*Atherigona soccata*), stem borers (such as *Chilo partellus* and *Busseola fusca*), armyworms (*Mythimna separata* and *Spodoptera spp.*), aphids (*Melanaphis sacchari*), and head caterpillars (*Helicoverpa armigera*) (Figure 2) (Okosun et al., 2021). These pests attack various parts of the plant, from the roots to the grain, and can cause substantial damage if not managed effectively. Diseases affecting sorghum include fungal infections, such as anthracnose and grain mold, which thrive in humid conditions and can lead to significant crop losses.

Figure 2 (A) Small colony of aphids on sorghum, (B) Corn leaf aphid and sugarcane aphids on sorghum (Photo: J. Scott Armstrong), (C) Adult sugarcane aphid adults in winged and wingless forms (Photo: P. Porter) (Adopted from Okosun et al., 2021)

5.2 Biological and chemical controls

Integrated pest management (IPM) strategies for sorghum involve a combination of biological and chemical controls. Biological control methods include the use of natural predators and parasitoids to manage pest populations. For instance, conservation practices that protect natural enemies at the landscape level are crucial for long-term pest management (Okosun et al., 2021). Chemical controls involve the application of pesticides, which can be chemical, botanical, or microbial in nature. However, the use of chemical pesticides should be carefully managed to avoid resistance development and environmental harm. An integrated approach that combines these methods is recommended to effectively control pest populations while minimizing negative impacts on the ecosystem (Okosun et al., 2021).

5.3 Breeding and genetic resistance

Breeding for pest and disease resistance is a critical component of sorghum cultivation. Host-plant resistance has been developed for several major pests, including the sorghum midge, greenbug, and aphids. Breeding programs have made significant progress in developing sorghum genotypes that exhibit resistance to multiple pests, such as combining resistance to shoot fly and stem borers. Genetic resistance is a sustainable approach to pest management, reducing the reliance on chemical controls and enhancing the resilience of sorghum crops to pest pressures. However, breeding for resistance to certain pest combinations, such as shoot fly versus midge, remains challenging and requires ongoing research and development.

6 Soil and Water Conservation Practices

6.1 Conservation tillage

Conservation tillage is a practice that minimizes soil disturbance, thereby preserving soil structure and moisture. In semi-arid regions like Northeast Nigeria, conservation tillage combined with mulching has been shown to significantly increase soil water storage and sorghum yield. The use of wood-shavings mulch, for instance, improved water use efficiency and grain yield by up to 77% compared to traditional flat bed cultivation without mulch (Chiroma et al., 2006). Similarly, in Eastern Ethiopia, tied ridges, a form of conservation tillage, improved soil water content and water-use efficiency when combined with nutrient management practices (Wondimu et al., 2024).

6.2 Water harvesting techniques

Water harvesting techniques are essential for capturing and utilizing rainwater efficiently, especially in regions prone to drought. In Zimbabwe, techniques such as tied contour and infiltration pits have been effective in increasing soil moisture content and rainwater use efficiency, leading to higher sorghum yields (Kugedera et al., 2022). These methods help in mitigating the effects of moisture stress and improving the resilience of sorghum crops to drought conditions. Additionally, in Burkina Faso, the combination of stone rows and grass strips with organic amendments like compost has been shown to enhance soil water storage and reduce runoff, thereby improving sorghum biomass production (Zougmoré et al., 2004).

6.3 Cover cropping and crop rotation

Cover cropping and crop rotation are practices that can improve soil fertility and structure, thereby enhancing water retention and reducing erosion. In the Texas High Plains, crop rotation involving sorghum and cotton has been used to optimize irrigation strategies and improve water use efficiency under varying climate conditions (Kothari et al., 2019). The integration of cover crops can also contribute to soil organic matter, which enhances soil moisture retention and nutrient availability. In semi-arid regions, the use of cover crops like Leucaena leucocephala has been shown to increase soil moisture content and sorghum yield, demonstrating the potential of these practices to improve agricultural sustainability (Kugedera et al., 2022).

7 Role of Technology in Sorghum Cultivation

7.1 Precision agriculture

Precision agriculture plays a crucial role in optimizing sorghum cultivation by enhancing resource use efficiency and crop management. The use of advanced models like the decision support system for agrotechnology transfer (DSSAT) allows for precise simulation of sorghum growth under varying environmental conditions. This system helps in determining optimal irrigation strategies, which are essential for maximizing yield and water use efficiency, especially in regions like the Texas High Plains where water resources are limited (Kothari et al., 2019). Additionally, machine learning and sensor-based technologies are being utilized to improve nitrogen use efficiency (NUE) in sorghum, which is vital for increasing yield and grain quality (Ostmeyer et al., 2022).

7.2 Decision support systems

Decision support systems (DSS) are integral in sorghum farming, providing farmers with data-driven insights to make informed decisions. The CERES-Sorghum module within DSSAT is a prime example, offering simulations that help in understanding the interactions between crop management practices and environmental factors. This system has been effectively used to model nutrient and water productivity in sorghum, aiding in the development of sustainable farming practices (MacCarthy et al., 2010). By simulating various scenarios, DSS can guide farmers in optimizing nitrogen application and irrigation schedules, thereby enhancing productivity and sustainability (White et al., 2015).

7.3 Mechanization in sorghum farming

Mechanization is another key aspect of modern sorghum cultivation, contributing to increased efficiency and reduced labor costs. The integration of mechanized systems in sorghum farming can significantly enhance productivity by optimizing planting, harvesting, and post-harvest processes. For instance, the use of advanced tillage methods and energy-efficient production systems has been shown to improve the agronomic performance of sorghum, as demonstrated in studies evaluating different tillage and fertilization strategies (López-Sandin et al., 2019). Moreover, innovations in sorghum transformation techniques, such as the GRF4-GIF1/ternary vector system, have accelerated genetic improvements, facilitating the development of high-yielding and resilient sorghum varieties (Li et al., 2023).

8 Case Study Sharing

8.1 Optimized cultivation model for high yield

Optimizing cultivation models for high yield in sorghum involves strategic management of irrigation, planting windows, and nutrient application. In the Texas High Plains, efficient irrigation strategies using the CERES-Sorghum model have been developed to optimize initial soil moisture and irrigation thresholds, significantly enhancing yield under varying climate conditions (Kothari et al., 2019). Similarly, in North-Eastern Nigeria, the APSIM crop model has been used to determine optimal planting windows for different sorghum cultivars, aligning sowing dates with climate-smart practices to maximize yield (Figure 3) (Akinseye et al., 2023). Additionally, the application of organic and inorganic fertilizers has been optimized using a Central Composite Design, achieving high yields by adjusting nitrogen, goat manure, and foliar fertilizer levels.

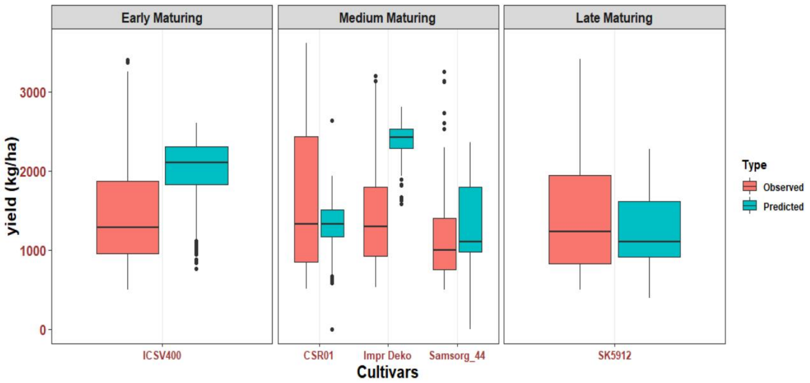

Figure 3 Yield (observed and simulated) using on-farm datasets from the 2013-2017 growing seasons from contrasting environments for five (5) sorghum cultivars ranged from early to late maturing. ICSV-400 (N = 1192; MBE = 535 kg·ha^{-1}; RMSE = 971 kg·ha^{-1}, CV = 13.8%); Improved Deko (N = 300; MBE = 960 kg·ha^{-1}, RMSE = 1169 kg·ha^{-1}, CV = 12.3%); Samsorg-44 (N = 100; MBE = 102 kg·ha^{-1}; RMSE = 655 kg·ha^{-1}, CV = 8.9%); CSR01 (N = 944; MBE = −228 kg·ha^{-1}, RMSE = 755 kg·ha^{-1}, CV = 25.5%); SK5912 (N = 731; MBE = −241 kg·ha^{-1}; RMSE = 879 kg·ha^{-1}, CV = 18.4%). Coefficient of variations (CV), N = number of observations (Adopted from Akinseye et al., 2023)

8.2 Sustainability-oriented cultivation

Sustainability in sorghum cultivation can be achieved through efficient water and nutrient management. In Central Greece, the use of subsurface drip irrigation has been shown to enhance water conservation and biomass production in sweet sorghum, demonstrating a sustainable approach to irrigation in dry years (Sakellariou-Makrantonaki et al., 2007). In Ghana, the use of mineral nitrogen fertilizers, combined with practices that retain soil organic matter, has been found to improve water use efficiency and stabilize yields, contributing to sustainable farming systems (MacCarthy et al., 2010). Furthermore, breeding for deeper-rooted sorghum cultivars in the southeastern USA has the potential to reduce irrigation needs by maximizing rainfall interception, promoting sustainability in rainfed systems (López et al., 2017).

8.3 Farmer-led innovations

Farmer-led innovations play a crucial role in adapting sorghum cultivation to local conditions. In the Brazilian Semiarid, experiments with different planting arrangements have identified optimal spacing for forage sorghum varieties, enhancing growth and productivity. In Ethiopia, the use of spatial model selection and design evaluation in sorghum breeding programs has improved the precision of genotype comparisons, allowing farmers to select the best-performing genotypes for their specific conditions (Tadese and Piepho, 2023). These innovations highlight the importance of local knowledge and experimentation in developing efficient and adaptable cultivation models for sorghum.

9 Challenges in Implementing Efficient Models

9.1 Resource constraints

Resource constraints significantly impact the implementation of efficient cultivation models for edible sorghum. One of the primary challenges is the limited access to essential inputs such as fertilizers and water. In sub-Saharan Africa, declining soil fertility and limited access to inorganic fertilizers lead to sub-optimal grain yields, which are further exacerbated by extreme weather conditions and climate change (Tonitto and Ricker-Gilbert, 2016). Additionally, the reliance on the Ogallala Aquifer for irrigation in regions like the Texas High Plains highlights the critical need for efficient water use to sustain agriculture (Kothari et al., 2019). The high cost of fertilizers also poses a challenge, as it affects the profitability of sorghum cultivation despite potential yield increases (Tonitto and Ricker-Gilbert, 2016).

9.2 Environmental and climatic challenges

Sorghum is known for its resilience to harsh environmental conditions, yet climate change presents significant challenges. Rising temperatures and increased CO_2 levels affect photosynthesis and water use efficiency in sorghum, complicating cultivation practices (Yang et al., 2024). In regions like north-eastern Nigeria, low soil fertility and early terminal droughts further constrain sorghum productivity, necessitating climate-smart management practices (Akinseye et al., 2023). Moreover, while sorghum is drought-tolerant, climate change could push its growing conditions beyond tolerable limits, threatening food security (Khalifa and Eltahir, 2023). Efficient irrigation management strategies are crucial, as weather conditions play a key role in selecting appropriate irrigation practices (Kothari et al., 2019).

9.3 Policy and market limitations

Policy and market limitations also hinder the optimization of sorghum cultivation models. The lack of supportive policies for resource allocation and market access can restrict the adoption of improved cultivation practices. In Africa, facilitating access to fertilizers and diversified crop rotations is essential for increasing grain yield, yet these practices are often limited by policy and market constraints (Tonitto and Ricker-Gilbert, 2016). Additionally, the global demand for bioenergy and food security pressures necessitate policies that support sustainable sorghum production (López-Sandin et al., 2019). Without adequate policy support, the potential benefits of technological advancements and improved management practices may not be fully realized.

10 Concluding Remarks

The optimization of efficient cultivation models for edible sorghum has been explored through various studies, highlighting the importance of irrigation management, planting windows, and nutrient use efficiency. Efficient irrigation strategies, such as those identified in the Texas High Plains, are crucial for maximizing yield and water use efficiency, especially under varying climate conditions. Optimal planting windows and cultivar selection, as demonstrated in North-Eastern Nigeria, are essential for adapting to climate change and improving sorghum productivity. Additionally, the integration of organic and inorganic fertilizers has been shown to significantly enhance sorghum yield, emphasizing the role of nutrient management in cultivation models.

Case studies have provided valuable lessons in optimizing sorghum cultivation. In the southeastern USA, breeding for deeper-rooted sweet sorghum cultivars has shown potential in reducing irrigation needs and increasing biomass yield, highlighting the importance of genetic improvements in cultivation strategies. In Central Greece, the use of subsurface drip irrigation has proven more effective than conventional methods, demonstrating the benefits of modern irrigation techniques in dry conditions. Furthermore, the exploration of native genetic variability for nitrogen use efficiency in sorghum has identified promising genotypes that perform well under low nitrogen conditions, offering insights into genetic selection for improved crop performance.

Future research should focus on further refining irrigation and nutrient management strategies to enhance sorghum yield and sustainability. The development of sorghum cultivars with improved drought tolerance and nutrient use efficiency should be prioritized to address the challenges posed by climate change and resource limitations. Additionally, expanding the use of advanced modeling techniques, such as those used in spatial model selection and design evaluation, can improve the precision of genotype comparisons and optimize field trial designs. Collaborative efforts across different agro-ecological zones will be essential to tailor cultivation models to local conditions and maximize the global impact of sorghum as a food and energy crop.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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