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Strategies for Enhancing Energy Utilization Efficiency of Sorghum

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Abstract This study summarized many methods to improve the energy utilization efficiency of *Sorghum bicolor*, including water management, farming methods, nutrient supply, biotechnology and biomass processing, etc. The results show that appropriately reducing irrigation and combining it with mulch can save water, increase yield and energy output, which is particularly effective in semi-arid and saline-alkali land. Adopting less tillage or no tillage at all, along with organic fertilizers, not only ensures stable production but also enhances energy utilization. In terms of biomass utilization, first ensiling sorghum residue with biofortification and then treating it with alkali can make it easier to decompose and utilize. Molecular breeding and bioengineering can also make sorghum more tolerant of adverse conditions such as iron deficiency and drought. Overall, integrating water, soil, nutrient management and biotechnology, and adjusting according to the conditions of different regions, is the core goal of improving the energy utilization efficiency of sorghum.
Keywords Sorghum; Energy utilization efficiency; Irrigation management; Biomass conversion; Molecular breeding

1 Introduction

Sorghum bicolor L. Moench is the fifth largest grain in the world. It has strong stress resistance and multiple uses, playing an important role in food, feed and renewable energy. It performs particularly well in adverse environments such as drought and saline-alkali conditions (Bakari et al., 2022; Zheng et al., 2023). In recent years, the global population has increased, climate change has intensified, and fossil energy has also been decreasing. In response to the pressure of energy and the environment, people have begun to attach importance to efficient and sustainable biomass energy crops (Bazaluk et al., 2021; Xiao et al., 2021; Ameen et al., 2024). Sorghum has a high yield, wide adaptability and can grow under low-input conditions. It is regarded as a good material for producing bioenergy (Xiao et al., 2021; Bakari et al., 2022).

Energy Utilization Efficiency (EUE) is an important indicator for measuring the relationship between the input resources and the output energy in the production and conversion processes of energy crops such as sorghum. Improving EUE can reduce energy consumption in agriculture, lower environmental pressure, and also enhance the economic viability and sustainability of the bioenergy industry. The factors influencing sorghum EUE include variety selection, farming methods, fertilization methods, irrigation methods, harvest time and processing techniques, etc. For instance, reducing input, optimizing irrigation and fertilization, using organic fertilizers or waste resources, and efficient biomass conversion technologies can all significantly enhance the energy output and utilization efficiency of sorghum (Wiedenfeld, 1984; Głąb et al., 2019; Lopez-Sandin et al., 2019; Jankowski et al., 2020; Perazzini et al., 2021; Xiao et al., 2021; Liu et al., 2024; Pietro Garofalo et al., 2025).

This review will systematically sort out and analyze the main methods and research progress for improving the EUE of sorghum in recent years, including aspects such as variety improvement, agronomic management, efficient resource utilization, and biomass conversion. We will analyze the energy input and output of different production systems, management measures and transformation paths to identify the key links and future directions for enhancing EUE. At the same time, the adaptability of sorghum in different ecological zones and its strategic value in global energy security and sustainable agriculture will also be discussed, providing references for the efficient utilization of sorghum and related policies.

2 Conceptual Framework of Energy Utilization Efficiency in Sorghum

2.1 Physiological basis

Sorghum bicolor L. Is an energy crop. It has a high yield, is drought-tolerant and can adapt to poor soil. The energy utilization efficiency of sorghum is mainly influenced by photosynthetic efficiency, water use efficiency (WUE), nutrient absorption and transformation efficiency, etc. During the growing season, the photosynthetic productivity and WUE of sorghum are both relatively high. In arid or semi-arid regions, its WUE can reach 3.04 kg C mm^{-1} H_2O, which is better than that of energy crops such as corn and miscanthus (Rinaldi, 2013; Garofalo and Enciso et al., 2019; Moore et al., 2021). The absorption and utilization efficiency of nitrogen also affects the biomass of sorghum and the theoretical ethanol yield. Moderate application of nitrogen can increase yield, but excessive application will reduce nitrogen utilization efficiency (Wiedenfeld, 1984).

2.2 Agronomic and environmental influences

The energy utilization efficiency of sorghum is influenced by factors such as fertilization, farming methods, water management and climatic conditions. Research has found that with minimal tillage and no fertilization, energy efficiency is the highest (up to 18.68). High input (such as a large amount of chemical fertilizers) can increase output, but energy efficiency will decline instead. The combination of organic and inorganic fertilizers, straw returning to the field and other practices can not only increase yield, but also optimize energy efficiency (Lopez-Sandin et al., 2019; Pashynska, 2019; Jankowski et al., 2020). In terms of water management, moderately reducing irrigation can improve the efficiency of water and energy utilization while maintaining production, especially suitable for the Mediterranean and arid regions (Garofalo and Rinaldi, 2013; Enciso et al., 2019; Pietro Garofalo et al., 2025). Environmental factors such as precipitation, temperature and soil type can also affect the biomass accumulation and energy conversion efficiency of sorghum (Enciso et al., 2019; Jankowski et al., 2020; Bazaluk et al., 2021).

2.3 Measurement methods

The energy utilization efficiency of sorghum is mainly measured by the following indicators:

Energy efficiency (EE): The ratio of output energy to input energy, used to measure energy conversion efficiency (Jankowski et al., 2020; Bazaluk et al., 2021).

Energy productivity (EP): The yield per unit of energy input ($kg \cdot MJ^{-1}$), reflecting the economy (Lopez-Sandin et al., 2019).

Specific energy consumption (SE): Energy required per unit of output ($MJ \cdot kg^{-1}$), indicating the level of production consumption (Brito et al., 2017; Okoro and Isa, 2021; Perazzini et al., 2021).

Net energy (NE): The difference between output energy and input energy, representing the surplus of the system (Jankowski et al., 2020).

Water use efficiency (WUE): Biomass or energy produced per unit of water consumption (Garofalo and Rinaldi, 2013; Enciso et al., 2019; Moore et al., 2021).

These data are derived from field experiments, energy input-output calculations, crop physiological measurements and mathematical model analyses, providing references for the evaluation and optimization of energy utilization efficiency of sorghum (Brito et al., 2017; Lopez-Sandin et al., 2019; Jankowski et al., 2020; Okoro and Isa, 2021; Perazzini et al., 2021).

3 Genetic Improvement Strategies

3.1 Breeding for high EUE traits

High EUE breeding is mainly aimed at enabling sorghum to grow more and utilize resources more efficiently. The key points include increasing biomass, adjusting plant structure and improving nitrogen utilization efficiency. Breeders will take advantage of natural genetic differences to select varieties that remain high-yielding under low-nitrogen conditions (Bollam et al., 2021; Ostmeyer et al., 2022) (Figure 1). For instance, genetic differences in leaf angles can alter the utilization efficiency of light in the canopy, thereby increasing yield and EUE (Truong et al., 2015). In addition, traits such as early maturity, high harvest index and high water use efficiency are also considered helpful for drought adaptation and improving EUE, and thus have been included in the comprehensive breeding goals (Zabuloni et al., 2025).

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)

3.2 Molecular and genomic tools

Methods such as molecular marker-assisted selection (MAS), genome-wide association analysis (GWAS), and genomic selection (GS) have greatly accelerated the improvement speed of high EE-related traits (Maqbool et al., 2001; Massel et al., 2016; Fernandes et al., 2017; Takanashi, 2023). High-throughput phenotypic analysis and next-generation sequencing technologies have also helped researchers better understand complex traits like NUE (Bollam et al., 2021). Combining genomic selection with related traits (such as plant height, leaf Angle, and dry matter accumulation) can improve the accuracy of prediction. Especially "character-assisted GS", the effect is more obvious when obtaining data in the early stage or at low cost (Fernandes et al., 2017). In addition, gene editing technologies such as CRISPR/Cas have been used to improve the stress resistance and nutrient utilization efficiency of sorghum (Nigam et al., 2025).

3.3 Examples from recent breeding programs

In recent years, hybrid varieties of energy sorghum have significantly increased biomass and EUE by adjusting phottoid response and extending vegetative growth period (Mullet et al., 2014). In terms of nitrogen utilization efficiency, whole genome sequencing has identified important genes related to nitrogen absorption and utilization, which provides molecular targets for breeding high NUE varieties (Massel et al., 2016). Combined selection of multiple traits and character-assisted genomic selection have demonstrated high consistency and high accuracy in the breeding of high-biomass sorghum (Fernandes et al., 2017). Furthermore, a number of high NUE genotypes have been screened out in different ecological types (for food, feed, and dual-use), and these resources are being used for molecular improvement and promotion of new varieties (Bollam et al., 2021).

4 Agronomic Management Strategies

4.1 Nutrient management

Reasonable nutrient management, especially the application of nitrogen fertilizer, is an important method to improve the energy utilization efficiency of sorghum. Research has found that an appropriate amount of nitrogen fertilizer can significantly increase the biomass and yield of sorghum. However, if applied in excessive amounts, it will reduce nitrogen utilization efficiency and also increase environmental pressure. The use of new types of fertilizers such as coated urea can enhance the utilization rate of nitrogen and increase production. Some studies suggest that under the current yield conditions, the application of coated urea at 120 kg N/ha can simultaneously optimize the yield and nitrogen utilization efficiency (Yan et al., 2022). In addition, the combined use of organic and inorganic fertilizers, such as the application of Leucaena green manure and NPK compound fertilizer together, can improve soil fertility, increase nutrient supply, thereby enhancing sorghum yield and energy utilization efficiency (Lopez-Sandin et al., 2019; Kugedera et al., 2022). It should be noted that low-input systems (such as no-tillage and less fertilization) perform better in terms of energy utilization efficiency, which indicates that while pursuing high yields, the balance between input and output should also be considered (Garofalo et al., 2018; Jankowski et al., 2020; Bazaluk et al., 2021) (Figure 2).


(a) (b) (c)

Figure 2 Sweet sorghum production: (a) a disc harrow; (b) shallow tillage; and (c) field studies (Adopted from Bazaluk et al., 2021)

4.2 Water-use optimization

Water management has a significant impact on the energy utilization efficiency of sorghum. Although full irrigation can achieve the highest biomass and ethanol yield, moderate deficiency irrigation can significantly improve water productivity and strike a balance between yield and sustainable water resource utilization (Pietro Garofalo et al., 2025). In semi-arid regions, the combination of rainwater collection and water retention measures (such as contour zones and seepage pits) with organic and inorganic fertilizers can significantly improve the rainwater utilization efficiency and agronomic efficiency of sorghum (Kugedera et al., 2022). In addition, sorghum itself has strong drought resistance and high water use efficiency, and performs better compared with energy crops such as corn and miscanthus (Moore et al., 2021; Khalifa and Eltahir, 2023).

4.3 Planting strategies

The planting method and variety selection are equally important for the energy utilization efficiency of sorghum. Different farming methods (such as traditional farming, minimum tillage, and no-tillage) and different sowing times will all affect the stability of yield and the energy input-output ratio. Studies have shown that minimum tillage and no-tillage combined with low fertilizer input can achieve higher energy utilization efficiency (Garofalo et al., 2018; Lopez-Sandin et al., 2019; Jankowski et al., 2020). In terms of variety selection, those hybrid species with strong adaptability and stable yield (such as Fadda and Nieleni) have high biomass and yield in various environments and are suitable for promotion in different ecological regions (Ndiaye et al., 2019). Furthermore, early sowing helps to utilize the dual uses of sorghum grain and biomass and maintain stable yields (Ndiaye et al., 2019).

5 Technological Innovations

5.1 Precision agriculture applications

Precision agriculture, by leveraging tools such as sensors, artificial intelligence, and high-throughput phenotypic analysis, can monitor the growth environment and nutrient requirements of sorghum in real time, thereby enabling rational input and enhancing energy utilization efficiency. Sensors and AI technologies have been used for high-throughput phenotypic analysis to help select varieties with high nitrogen utilization efficiency (NUE), and to formulate management methods suitable for different environments, thereby significantly increasing yield and resource utilization (Ostmeyer et al., 2022; Liu et al., 2024). In addition, by using molecular markers and multi-omics analysis, researchers identified genes associated with high NUE, providing theoretical support for the precise breeding of high-efficiency sorghum varieties (Liu et al., 2024). In field management, the use of new controlled-release fertilizers (such as polyaspartic acid-coated urea) can improve nitrogen utilization and crop yield, while reducing environmental losses and achieving a balance between high yield and high energy efficiency (Yan et al., 2022).

5.2 Bioenergy-oriented approaches

The improvement of energy utilization efficiency of sorghum in bioenergy mainly relies on means such as biomass management, conversion processes and bioengineering. In biomass management, replacing urea with digestive juices and sludge can increase the output and energy efficiency ratio of biofuels such as methane and ethanol, which is particularly effective in temperate climates (Jankowski et al., 2020). In bioconversion processes, new methods such as nanotechnology and enzyme immobilization can significantly increase the yield and conversion efficiency of ethanol, while reducing energy consumption and costs (Cadiz et al., 2023; Punia and Kumar, 2024). Thermochemical treatments (such as pyrolysis and roasting) can increase the energy density and fuel quality of sorghum biomass, providing a new approach for the production of solid biofuels and high value-added chemicals (Yue et al., 2017; Ameen et al., 2024). Furthermore, molecular biology and genetic engineering methods have been employed to improve the stress resistance and nutrient absorption capacity of sorghum, which enables it to have greater energy utilization potential even in marginal land and adverse environments (Senoura et al., 2024; Zabuloni et al., 2025).

6 Environmental and Socioeconomic Considerations

6.1 Adaptation to climate variability

Sorghum can adapt to extreme climates such as drought, high temperature and waterlogging, and is thus called "the camel among grains". Under the background of climate change, it shows strong climate resilience and is an important crop for ensuring food security and the livelihoods of smallcap farmers (Chadalavada et al., 2021; Hossain et al., 2022; Khalifa and Eltahir, 2023; Wibowo and Meylani, 2024). Many simulations and field studies have shown that measures such as integrated soil fertility management (ISFM), agroforestry, new varieties with stress tolerance and irrigation can significantly increase sorghum yield. In some areas, the increase in yield can even reach 300% (Akinseye et al., 2020; Mohammed and Misganaw, 2022; Arumugam et al., 2023; Khalifa and Eltahir, 2023) (Figure 3). Research on the combination of genome and environment has found that sorghum has rich genetic diversity and adaptive loci in different ecological regions, which provides a theoretical basis for breeding varieties that are more resistant to climate change (Menamo et al., 2020; Takanashi, 2023; Mukherjee et al., 2024; Mwamahonje et al., 2024). In regions with variable climates such as Africa and South Asia, promoting sorghum can help reduce the food and nutritional risks brought about by climate variation.

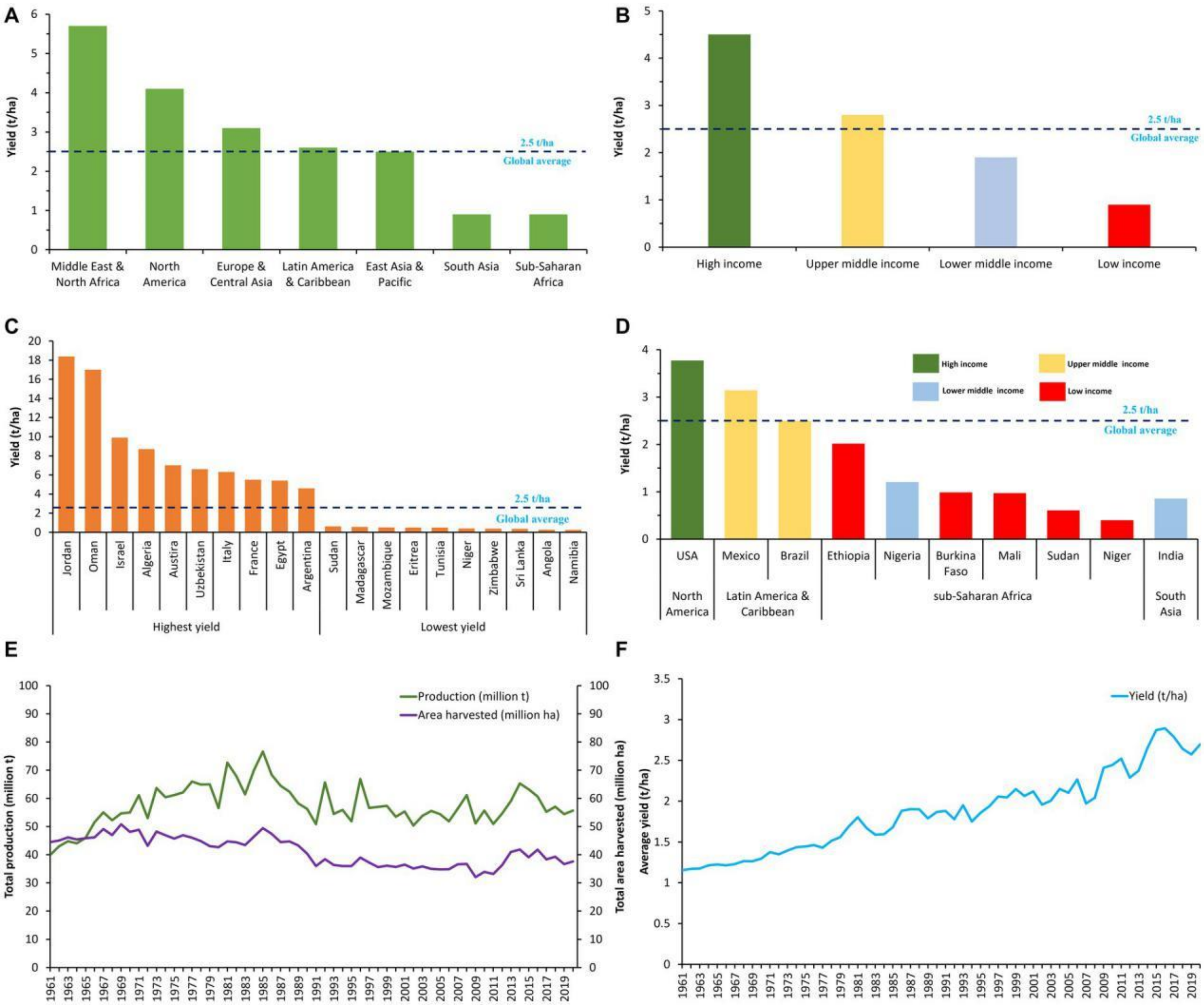

Figure 3 Multi-year (2001-2020) average yield of sorghum: region-wise (A); economy-wise (B); 10 countries with the highest and lowest yield (C); top 10 countries with sorghum harvested area (D); time series of global sorghum production (in million tonnes) and area harvested (in million ha) for 1961-2020 (E); and time series of average yield on a global scale for 1961-2020 (F) (Adopted from Khalifa and Eltahir, 2023)

6.2 Sustainability and smallholder adoption

Sorghum has low input and high output, making it an important choice for small-scale farmers to achieve sustainable livelihoods. However, in many places, the proportion of adopting improved varieties and efficient management techniques is not high. The reasons include insufficient credit, difficulty in purchasing seeds, inadequate technical services and difficulty in market access (Tonitto and Ricker-Gilbert, 2016; Mwangi et al., 2020; Dunjana et al., 2022; Onuwa, 2023; Kamara et al., 2025). Research has found that variety information acquisition, distance from the seed market, agricultural credit and technology extension services are important factors affecting the adoption by smallholder farmers (Mwangi et al., 2020; Onuwa, 2023; Kamara et al., 2025). Intercropping, crop diversification, and rational use of fertilizers and organic matter can not only increase yield, but also enhance the risk-resistance capacity and economic stability of the system (Tonitto and Ricker-Gilbert, 2016; Onuwa, 2023). Diversified practices such as crop rotation of leguminous crops can also increase yields and bring higher economic returns (Tonitto and Ricker-Gilbert, 2016).

6.3 Policy and extension support

A sound policy and promotion system is of great significance for enhancing the energy efficiency of sorghum and promoting sustainable development. Strengthening policy support, enhancing promotion and service capabilities, and improving market access and credit conditions all contribute to promoting the popularization and industrialization of sorghum technology. Specific measures include: increasing investment in variety research and development and promotion, improving the supply chain of seeds and agricultural supplies, implementing price support and crop insurance, and strengthening farmer training and information services (Dunjana et al., 2022; Onuwa, 2023; Kamara et al., 2025; Khaskheli et al., 2025). Meanwhile, social policies should also focus on groups such as the labor force, gender and youth, and promote inclusive agricultural development, thereby enhancing the overall resilience and sustainability of the sorghum production system (Khaskheli et al., 2025).

7 Case Study: Improving EUE in Sorghum in the Mediterranean Region

7.1 Background

The climate in the Mediterranean region is generally dry, with little precipitation and a shortage of water resources. Take Apulia in southeastern Italy as an example. There is an urgent need to develop efficient and sustainable bioenergy crops there. *Sorghum bicolor* L. Moench has strong drought resistance and high adaptability, and thus is regarded as an ideal crop for the development of bioenergy here (Pietro Garofalo et al., 2025).

7.2 Intervention details

This case adopted three irrigation methods: full irrigation, deficit irrigation and regulated deficit irrigation. The regulation of irrigation volume, combined with standard crop coefficients and soil moisture monitoring, has achieved precise water supply. Studies were conducted in 2013, 2014 and 2017 to systematically evaluate sorghum biomass, ethanol production and water use efficiency under different irrigation conditions (Pietro Garofalo et al., 2025).

7.3 Outcomes

Under full irrigation conditions, the biomass and ethanol yield of sorghum were the highest, with the biomass ranging from 22 633 to 28 367 kg/ha, and the ethanol yield also increased significantly. However, in terms of water productivity, deficient irrigation performed better, with biomass water productivity reaching 10.93 kg/m^3 and ethanol water productivity reaching 3.23 L/m^3. This indicates that underirrigation can make better use of limited water resources while ensuring production (Pietro Garofalo et al., 2025).

7.4 Lessons learned and scalability

Studies show that moderate deficiency irrigation can not only save water but also improve the energy utilization efficiency of sorghum. This approach is particularly suitable for promotion in the Mediterranean and other semi-arid regions where water resources are tight. Important experiences include: flexibly adjusting irrigation plans based on local climate and soil conditions, and optimizing water management in combination with precise monitoring. This model has strong scalability and can also provide a reference for the utilization of sorghum energy in similar ecological zones worldwide (Pietro Garofalo et al., 2025).

8 Future Prospects and Research Gaps

8.1 Integration of genomic, agronomic, and technological innovations

At present, improving the energy use efficiency (EUE) of sorghum mainly relies on the improvement of agronomic management (such as irrigation, tillage, and fertilization) and biomass pretreatment technology. However, the combination of genomics and precision agriculture technology is still in its early stages. In the future, it is necessary to integrate the genomic information of sorghum with agronomic measures (such as reduced tillage, straw mulching, and microbial enhanced fermentation, etc.) to promote collaborative innovation. Meanwhile, the combined application of high-throughput phenotypic analysis, molecular breeding and intelligent management systems should be strengthened to enable the continuous improvement of EUE (GCL et al., 2019; Lopez-Sandin et al., 2019; Rai et al., 2022; Ren et al., 2024).

8.2 Long-term multi-environment trials to assess stability of EUE gains

Most of the current research is energy efficiency assessment conducted in a single or short-term environment, lacking systematic trials involving multiple years and multiple ecological zones. In the future, long-term field trials should be carried out under different climate zones, soil types and multiple management models to systematically evaluate the stability and adaptability of EUE improvement measures. Meanwhile, it is necessary to analyze the interaction between the environment and management measures to provide a scientific basis for the promotion of sorghum EUE in different regions (Jankowski et al., 2020; Rai et al., 2022; Pietro Garofalo et al., 2025).

8.3 Development of cost-effective tools for smallholder farmers

Nowadays, the EUE improvement technology for sorghum is more widely applied in large-scale farms, while small-scale farmers find it difficult to promote it due to limited funds, technology and equipment. In the future, it is necessary to focus on developing low-cost and easy-to-operate management tools, such as simple irrigation control, low-input biomass pretreatment methods, and the use of local resources to replace organic fertilizers. Meanwhile, it is necessary to strengthen technical training and demonstration to increase the adoption rate and economic benefits of small-scale farmers. (Lopez-Sandin et al., 2019; Jankowski et al., 2020; Ren et al., 2024).

8.4 Climate change modeling for sorghum EUE projections

Climate change will bring uncertainties to the growth environment and energy utilization efficiency of sorghum. Future research should integrate climate models to simulate the changing trends of sorghum EUE under different temperature, precipitation conditions and extreme climate events. Meanwhile, the effects of adaptive management measures should be evaluated to provide scientific references for policy-making and planting structure adjustment (Bazaluk et al., 2021; Pietro Garofalo et al., 2025).

9 Concluding Remarks

The main methods to enhance the energy utilization efficiency of sorghum include: improving irrigation management, optimizing fertilization plans, applying efficient tillage and mulching measures, developing biofortification and pretreatment technologies, as well as conducting genetic improvement and molecular breeding. Moderate deficiency irrigation can save water, maintain production, and improve the efficiency of water and energy utilization, making it suitable for sustainable development in arid and semi-arid regions. The rational use of organic and inorganic fertilizers and the return of farmland straw to the field can increase biomass, grain production and biofuel output, while making energy input and output more reasonable. Adopting methods such as minimum tillage, covering crop residues, and reduced tillage can improve soil structure, increase energy output, and enhance the stability of the system. In terms of biomass pretreatment, the combination of bioenhanced silage and alkaline pretreatment can significantly improve the degradability and enzymatic hydrolysis efficiency of sorghum straw, providing a new approach for efficient conversion into bioenergy. In addition, molecular breeding and genetic engineering, such as enhancing resistance to iron deficiency and nitrogen utilization efficiency, are also strengthening the production capacity of sorghum under adverse conditions.

Studies show that it is difficult for a single measure to fully exploit the energy utilization potential of sorghum. The future requires the integration and innovation of multiple fields such as agronomy, molecular biology, ecological environment and engineering technology. For instance, by integrating precise irrigation, intelligent fertilization, genetic improvement and high-throughput phenotypic analysis, the energy utilization efficiency of sorghum can be more systematically enhanced. At the same time, promoting the resource utilization of waste (such as returning digestive juices and sludge to the fields) and green production methods will help establish a low-carbon and circular agricultural energy system.

Sorghum is drought-tolerant and salt-tolerant, with low input and high yield. It is an important crop for ensuring food security and developing bioenergy on arid, semi-arid and marginal land. By continuously optimizing energy utilization efficiency, sorghum is expected to play a greater role in the transformation of the global food and energy systems and contribute to achieving the goals of carbon neutrality and sustainable development.

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Conflict of Interest Disclosure

The author affirms 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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