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Feasibility Study of Using Sorghum Biomass for Fuel Ethanol Production

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Abstract This study looked at whether sorghum can be used to make fuel ethanol. We tried to analyze it from several aspects, such as the ethanol yield of different sorghum varieties, their chemical composition, and how to treat them best. The study found that sorghum has a high yield, is drought-resistant, and can adapt to different environments. This makes it suitable for planting in many places and making bioethanol. In addition to the main part of the sorghum, its field waste, such as straw, and by-products, such as sweet sorghum juice and residue, can also be used to ferment ethanol. We tried several treatment methods, including pretreatment with organic solvents, alkali, acid, or enzymes. These methods can release more sugar and increase ethanol production. Some methods can also use biodiesel by-products, which can save a lot of costs. If all these field residues and by-products are used, not only will they not compete with food for land, but they will also reduce waste and be more environmentally friendly. In this way, not only can we develop bioenergy, but we can also help protect the environment and achieve a "win-win" situation. We also did an economic analysis. The results show that if the processing technology and enzyme costs can be optimized, the price of ethanol made from sorghum may be similar to that of gasoline. In this case, it has a good chance of being promoted for industrial use.
Keywords Sorghum biomass; Fuel ethanol; Pretreatment; Yield assessment; Sustainable energyy

1 Introduction

Nowadays, the world is in greater and greater demand for renewable energy. In order to cope with climate change and energy shortage, everyone is trying to find some environmentally friendly energy that can replace oil. Bioethanol is one of the popular choices because it can reduce pollution and help rural economic development. However, most bioethanol is now made from food crops such as corn and sugarcane. This brings up a problem: if food is used as fuel, it may conflict with people's need to eat. Therefore, it is particularly important to find a raw material that is not a food. This review mainly wants to see whether sorghum can be a suitable raw material for bioethanol. We will analyze it from multiple aspects, such as its application prospects, technical difficulties, and its possibilities in this industry.

As people increasingly need clean energy, bioethanol has become an important option to replace traditional fuels because of its environmental protection and renewable nature (Prasad et al., 2007; van Rijn et al., 2018). But the problem is that the raw materials used now are mostly corn and sugarcane, which will compete with food production for land, and the price will also fluctuate. Therefore, scientists began to look for new materials to make ethanol. Sorghum is a good choice. It is drought-resistant, high-yielding, and highly adaptable. It can be grown in marginal lands and places where it is difficult to grow crops. It is also rich in cellulose and sugar, making it a good material for ethanol (Ekefre et al., 2017; Rivera-Burgos et al., 2019; Batog et al., 2020). Although many people have begun to study the possibility of sorghum for ethanol, research in this area is not comprehensive enough. In particular, more can be done in terms of different climates, variety selection, and how to use waste materials (Sathesh-Prabu and Murugesan, 2011; Boboescu et al., 2019; Batog et al., 2020).

This study will first introduce several types of sorghum biomass and their basic characteristics. Next, we will talk about the new progress in sorghum pretreatment methods and saccharification technology. We will also look at how different sorghum varieties and planting methods affect ethanol production. Then, we will talk about the use cases of sorghum in different climate conditions and its economic feasibility. Finally, we will summarize the advantages, difficulties and future development directions of sorghum in fuel ethanol production.

2 Overview of Sorghum as a Biomass Crop

2.1 Types of sorghum: grain sorghum vs. sweet sorghum vs. forage sorghum

Sorghum (*Sorghum bicolor*) is a crop that can be used as biomass energy. It can be roughly divided into three types: grain sorghum, sweet sorghum and fodder sorghum. Grain sorghum is mainly used to produce food. The stems of sweet sorghum contain a lot of sugar, which is easily fermented into ethanol, so it is a good material for making bioethanol. Fodder sorghum has a high yield and is palatable. It is often used as feed. It can also be used to generate electricity or make other biomass energy (Prasad et al., 2007; Ekefre et al., 2017; Batog et al., 2020). Among these three types, sweet sorghum is widely used in the production of ethanol fuel because of its high sugar content and high yield (Prasad et al., 2007; Ekefre et al., 2017).

2.2 Agronomic advantages

2.2.1 Drought tolerance

One of the most prominent advantages of sorghum is that it is very drought-resistant. It can grow well even in places where there is not much water. Especially in marginal or arid and semi-arid areas, it can survive better than many other crops (Prasad et al., 2007; Batog et al., 2020). Compared with corn and sugarcane, which require a lot of water, sorghum is a good alternative that saves a lot of water.

2.2.2 Low input requirements

Growing sorghum does not require a lot of fertilizer or pesticides. It is efficient in using water and can adapt to relatively harsh growing environments (Prasad et al., 2007; Ekefre et al., 2017). This means that the cost of growing sorghum is relatively low and the pressure on the environment is also small (Prasad et al., 2007).

2.2.3 Versatile cultivation regions.

Sorghum is highly adaptable. It can be grown in temperate, subtropical and even tropical areas. It can grow well and have good yields even in less fertile or saline soils (Prasad et al., 2007; Ekefre et al., 2017; Batog et al., 2020). Some studies have found that in temperate regions such as Central and Eastern Europe, sorghum can produce a lot of biomass and ethanol, whether as a main crop or a rotation crop (Batog et al., 2020).

2.3 Biomass yield potentials

Sorghum has a considerable yield, especially some varieties, whose ethanol yield can be similar to or even higher than that of traditional energy crops such as sugarcane (Ekefre et al., 2017; Boboescu et al., 2019; Rivera-Burgos et al., 2019). The theoretical ethanol yield of the sweet sorghum variety Theis can reach 7 619 liters per hectare. Moreover, different sorghum varieties and different planting conditions will result in very different biomass and sugar content. This difference also provides room for breeding, which can be further improved to increase yield (Ekefre et al., 2017; Rivera-Burgos et al., 2019). The straw and field waste left after sorghum harvest can also be used to make cellulosic ethanol. These "leftovers" do not affect food production, but can be turned into treasures, which are very useful resources (Sathesh-Prabu and Murugesan, 2011; Boboescu et al., 2019; Rivera-Burgos et al., 2019).

3 Composition and Bioconversion Properties of Sorghum Biomass

3.1 Chemical composition: cellulose, hemicellulose, lignin content

Sorghum biomass, including sweet sorghum stalks, residues and bran, contains three main components: cellulose, hemicellulose and lignin. For example, sweet sorghum residue contains about 29.34% lignin, 17.75% cellulose, and 16.28% hemicellulose (Mafa et al., 2020) (Figure 1). The cellulose content of sorghum bran is 11%, hemicellulose is 18%, and lignin is relatively less (Corredor et al., 2007). The composition of sorghum from different varieties and different parts will be slightly different. But in general, sorghum contains less cellulose and hemicellulose than corn stalks and sugarcane bagasse, while lignin is higher (Corredor et al., 2007; Mafa et al., 2020; Xu et al., 2020).

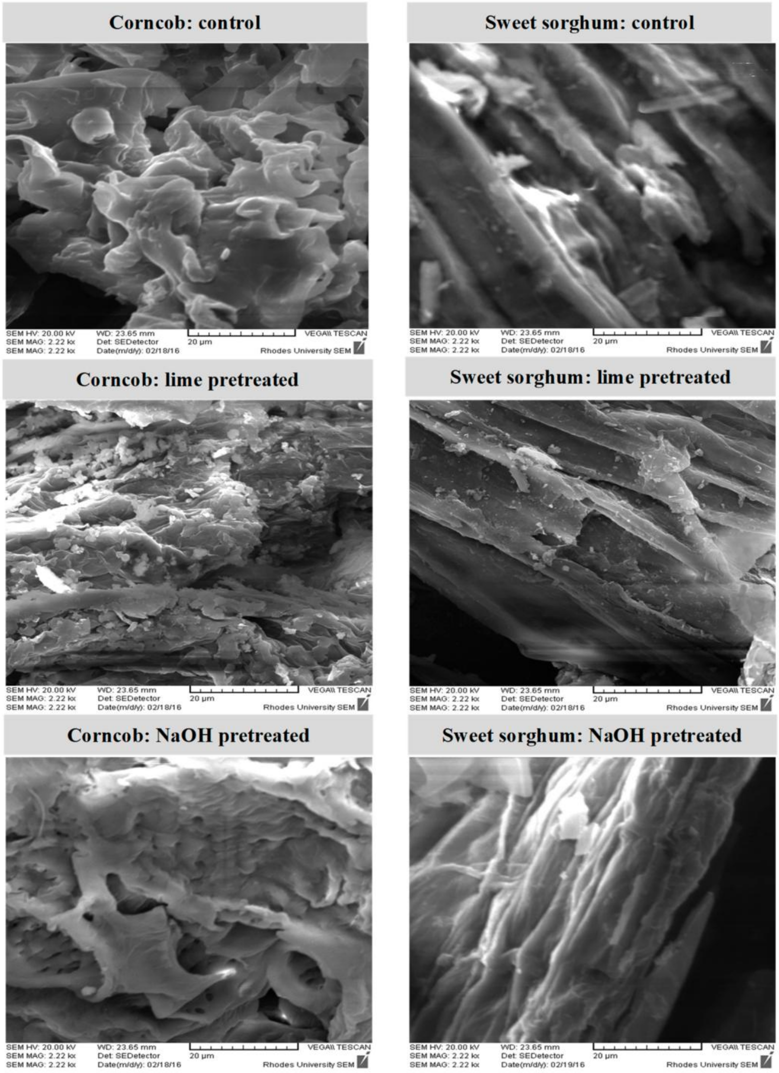

Figure 1 Topological analysis of pretreated sweet sorghum (SSB) and corncob (CC) feedstocks using scanning electron microscopy (SEM). The captions above the images indicate the control (untreated), type of treatment and the biomass in each SEM image. The scale bar was 20 µm and the magnification was 2.22 kx (Adopted from Mafa et al., 2020)

3.2 Suitability for bioconversion: comparison with corn stover, sugarcane bagasse, etc.

Compared with corn stover, sweet sorghum bagasse has lower cellulose and hemicellulose contents, but higher lignin contents. For example, corn stover has 23.58% cellulose, 33.34% hemicellulose, and 22.51% lignin (Mafa et al., 2020). More lignin usually makes conversion more difficult. However, if sorghum biomass is treated with appropriate methods first, the saccharification rate can exceed 80%. This shows that it still has good conversion potential (Rao and Binod, 2014; Dong et al., 2019; Xu et al., 2020). Like sugarcane bagasse, cellulose can be retained after sorghum is treated with alkali or acid, while lignin and hemicellulose can be effectively removed, making it easier to enzymatically hydrolyze later (Santos et al., 2021; García-Negrón et al., 2024). After pretreatment with dilute sulfuric acid, the glucose enzymatic hydrolysis rate of some sorghum mutants can reach 82.4%, which is similar to that of well-treated corn straw and sugarcane bagasse (Xu et al., 2020).

3.3 Challenges in pretreatment and enzymatic hydrolysis

Sorghum has a lot of lignin and a complex cell wall structure, which is the main difficulty encountered in bioconversion. To improve the conversion rate, pretreatment must be done first. For example, the alkaline method, acid method, hydrogen peroxide method, or "silage + alkaline method" can remove a lot of lignin and hemicellulose, making cellulose easier to be decomposed by enzymes (Dong et al., 2019; Santos et al., 2021; García-Negrón et al., 2024; Zhao et al., 2024; Bhati and Sharma, 2025). Among these methods, treatment with 2%

NaOH has the best effect. It can effectively remove lignin and achieve an enzymatic hydrolysis rate of 87.7% (Bhati and Sharma, 2025). If silage is first used and then pretreated with NaOH, it can not only reduce the loss during the fermentation process, but also increase the sugar yield. Some experiments even reached 94.45% (Zhao et al., 2024). These treatment methods also have problems, such as using more energy and chemicals, and producing some inhibitors, which are not conducive to large-scale production (Rao and Binod, 2014; Dong et al., 2019; Santos et al., 2021). The lignin and cellulose of sorghum are too tightly attached, which makes it easy for the enzyme to stick to it and "work in vain", which will reduce the conversion efficiency. Therefore, it is necessary to further improve the efficiency of delignification and optimize the amount and type of enzymes used to truly solve this problem (Dong et al., 2019; Bhati and Sharma, 2025).

4 Pretreatment and Processing Technologies

4.1 Mechanical, thermal, and chemical methods: steam explosion, dilute acid, alkaline, ionic liquids

Pretreatment is a critical step to make sorghum biomass easier to convert into sugars and ethanol. It can break up the hard wood fiber structure, help release more sugars, and achieve better fermentation results. Mechanical and thermal methods are more common, such as steam explosion and liquid hot water treatment (LHW). These methods use high temperature and pressure to destroy cell walls, making it easier for subsequent enzymes to enter and decompose (Bedzo et al., 2022; Kreetachat et al., 2025). Chemical methods are also commonly used, such as using dilute acids (such as sulfuric acid and hydrochloric acid) or alkalis (such as sodium hydroxide and ammonia), as well as alkaline hydrogen peroxide. These methods can remove most of the lignin and some of the hemicellulose, making cellulose more accessible (Chen et al., 2012; Koradiya et al., 2016; Santos et al., 2021; Batog and Wawro, 2022; Saïed et al., 2024). Recently, there are also some new methods, such as using ionic liquids or organic solvents (such as glycerol and ethanolamine) to treat sorghum. These solvents perform well in delignification and releasing sugars (Joy et al., 2021; Joy and Krishnan, 2022).

4.2 Recent advances in sorghum-specific pretreatment

In recent years, there have been many new advances in pretreatment methods designed specifically for sorghum. The organic solvent method using a mixture of glycerol and ammonia can also clean up lignin very well and release more sugars at low temperatures. More importantly, the glycerol used can come from the byproduct of biodiesel, which can also save money (Joy et al., 2021; Joy and Krishnan, 2022). Another method is "microwave + ammonia" treatment. It can make the structure of sorghum looser and remove more lignin, which ultimately improves the efficiency of saccharification and fermentation (Chen et al., 2012). Another technology is called ammonia fiber expansion (AFEX), which can produce more sugar and ethanol at high solid content after optimization (Li et al., 2010). Some people have also tried to combine alkaline hydrogen peroxide with some enzymes (such as laccase). This combination not only has a good delignification effect, but is also more environmentally friendly (Santos et al., 2021; Batog and Wawro, 2022).

4.3 Impacts on sugar yield and fermentability

Different pretreatment methods have a great influence on sugar output and fermentation effect. Dilute acid and alkaline hydrogen peroxide pretreatment can well retain polysaccharides and remove lignin. After treatment, the yields of glucose and xylose can be increased, up to 91.09% and 88% (Santos et al., 2021; Saïed et al., 2024; Kreetachat et al., 2025). Using modified organic solvent method or ammonia water pretreatment can also make cellulose better decomposed by enzymes, and the digestibility can reach 72% to 89%. The total sugar yield can be as high as 421.35 mg/g, and the maximum ethanol can reach 42.3 g/L (Li et al., 2010; Joy et al., 2021; Joy and Krishnan, 2022). Methods such as "microwave + ammonia water" or liquid hot water method can also produce a lot of sugar and ethanol without high enzyme dosage (Chen et al., 2012; Kreetachat et al., 2025). Moreover, these treatment methods do not produce many inhibitors, making them more suitable for fermentation (Koradiya et al., 2016; Santos et al., 2021). Different sorghum varieties respond differently to various pretreatment methods. Therefore, it is necessary to adjust the treatment conditions according to the characteristics of the specific variety in order to obtain the most sugar and ethanol (Joy et al., 2021).

5 Microbial Fermentation for Ethanol Production

5.1 Microorganisms used: yeast (e.g., *Saccharomyces cerevisiae*), engineered strains

There are two types of microorganisms commonly used in the process of converting sorghum biomass into ethanol. One is traditional yeast, such as *Saccharomyces cerevisiae*; the other is engineered bacteria. Studies have found that if the conditions are well controlled, *S. cerevisiae* can produce about 68 grams per liter of ethanol from sorghum straw. Another yeast, *Pachysolen tannophilus*, can also produce about 56 grams per liter of ethanol (Sathesh-Prabu and Murugesan, 2011). In addition to yeast, scientists have also used some engineered strains of Escherichia coli. These bacteria can process both hexose and pentose sugars, which increases ethanol production and allows for more efficient use of raw materials (van Rijn et al., 2018).

5.2 Inhibitors from sorghum processing: fermentation challenges due to phenolics and acids

During the process of processing and decomposing sorghum biomass, some byproducts, such as phenols and organic acids, are produced. These substances interfere with the fermentation process, hinder the normal growth of microorganisms, and reduce ethanol production (Batog and Wawro, 2022; Joy and Krishnan, 2022). Some pretreatment methods slow down yeast metabolism, which in turn affects ethanol production. To improve the yield, it is necessary to study better treatment methods to remove these inhibitors.

5.3 Strategies for optimization: co-fermentation, fed-batch, immobilization

In order to reduce the impact of inhibitors and to produce more ethanol, researchers have tried many improvement methods. One is co-fermentation, such as "simultaneous saccharification and fermentation" (SSCF). This method can utilize hexose and pentose sugars at the same time, making the utilization rate of sugar higher and increasing ethanol production (van Rijn et al., 2018; Joy and Krishnan, 2022). Another is fed-batch fermentation. This method is suitable for use when there are a lot of solid materials. It can help microorganisms maintain their vitality and increase the ethanol concentration. For example, under the condition of 20% solid loading, the yield can reach 36 grams per liter (Joy and Krishnan, 2022). There is also cell immobilization technology. This method can make microorganisms more resistant to inhibitors, and the fermentation process is more stable and efficient (Sathesh-Prabu and Murugesan, 2011; Joy and Krishnan, 2022).

6 Environmental and Economic Considerations

6.1 Life cycle assessment (LCA): GHG reduction potential, water and land use

Sorghum has performed well in reducing greenhouse gas emissions when used to produce fuel ethanol. Many LCA studies have found that using sweet sorghum or grain sorghum to make ethanol can reduce greenhouse gas emissions by more than half compared to gasoline. If combined with a combined heat and power (CHP) system and recycling by-products (such as distiller's grains and liquid fertilizers), the emission reduction effect can be increased to more than 70% (Cai et al., 2013; Spatari et al., 2018). Compared with traditional raw materials such as corn, sorghum has similar emission reduction capabilities, and in some places even better (Cai et al., 2013; Spatari et al., 2018; Kent et al., 2020). Sorghum is also more drought-tolerant and has strong adaptability. It can be planted in marginal land and will not compete with food crops for good land and water, which helps alleviate the problem of "food and energy competing for land" (Rivera-Burgos et al., 2019; Batog et al., 2020).

6.2 Economic feasibility: cost breakdown: cultivation, processing, infrastructure

For sorghum ethanol to be profitable, it depends on several key costs. For example, planting, harvesting, transportation, and subsequent pretreatment, enzymatic hydrolysis, fermentation, and the cost of building a factory (van Rijn et al., 2018; Wirawan et al., 2024). In 2018, Vermerris' team conducted a study and analysis and found that if the sweet sorghum residue is properly handled, the price of the ethanol it produces can be close to the energy equivalent price of gasoline. If the cost of enzymes is reduced in the future, or the by-products are better developed, the economic benefits will be even higher (van Rijn et al., 2018). In some countries such as Indonesia, there are some small sorghum ethanol plants. These factories use the entire sorghum plant, including the grains, leaves and residues, to produce not only ethanol but also many other products. The return on investment of these factories can reach 28%, and the cost can be recovered in 4 years, which shows that this model is also quite cost-effective (Wirawan et al., 2024).

6.3 Co-products and value-added streams

In the process of making ethanol, many by-products are produced. For example, distiller's grains, distiller's grains liquid fertilizer, sorghum powder, sorghum bran, pellet fuel, etc. (Cai et al., 2013; Wirawan et al., 2024). These things are not waste and can continue to be used. They can be used as animal feed, organic fertilizer, or used to generate electricity. Some can also enter the food or biomaterial market. Using these by-products can not only share part of the production costs, but also help reduce greenhouse gas emissions and improve resource utilization efficiency (Cai et al., 2013; van Rijn et al., 2018; Wirawan et al., 2024). Returning distiller's grains to the fields can reduce the use of chemical fertilizers and make the soil healthier, which is a practice that is conducive to recycling (Cai et al., 2013).

7 Policy, Market, and Adoption Barriers

7.1 Current policy landscape: renewable fuel standards, subsidies

Some current policies, such as the Renewable Fuel Standard (RFS), set high targets for cellulosic ethanol. However, the actual situation is far from expectations. For example, in the United States, cellulosic fuel production in 2017 only achieved 5% of the original target (Cui et al., 2018). There are many reasons. One is that farmers are unsure about growing high-yield crops that require many years of cultivation (such as sorghum), and they are worried that the investment is too high and it is not cost-effective. Another problem is that policies and markets change frequently, and people dare not invest money to build those large new ethanol plants. Policy requirements for greenhouse gas emission reduction have also affected the opportunity for sorghum ethanol to enter the market. A simulation study found that the emission reduction effect of sorghum ethanol is similar to that of corn. If sorghum yields are not high enough, it will be difficult to meet the emission reduction standards set by RFS for cellulosic fuels (Kent et al., 2020).

7.2 Market dynamics: price volatility, feedstock competition

Whether sorghum ethanol can make money depends largely on its price competitiveness with gasoline. Some technical and economic analyses point out that if the price of enzymes can be reduced or byproducts such as lignin can be effectively utilized, then the minimum selling price of sorghum ethanol may be close to the energy equivalent price of gasoline (van Rijn et al., 2018). Otherwise, it will need to rely on policy subsidies or wait for oil prices to rise. Another big problem is the supply chain of raw materials. Raw materials such as sorghum are seasonal, not easy to store, and the transportation cost is not low. All these limit the expansion of the sorghum ethanol market (Jiang et al., 2024). Taking China as an example, if the output of raw materials decreases or the demand for ethanol suddenly increases, the cost and carbon emissions of the entire supply chain will increase. However, some pressure can be alleviated through more reasonable factory layout and the use of railway transportation.

7.3 Adoption challenges for farmers and industry

Farmers still have many concerns when growing new energy crops such as sorghum. Many people are reluctant to try new crops because they are worried about unstable yields, unfamiliarity with technology, and high risks. Moreover, they are used to the original planting methods and are not sure whether the sorghum market is stable or not, and whether the price is reliable (Cui et al., 2018). On the other hand, it takes a lot of money to build or transform a biorefinery. In addition, the market and policies change frequently, so companies are reluctant to invest rashly (Cui et al., 2018; van Rijn et al., 2018). From the perspective of the supply chain, how to collect, deliver and process the raw materials at the right time while controlling costs is also a big problem (Jiang et al., 2024) (Figure 2). Although sorghum can be grown on marginal land and will not compete with grain for land, if this industry is to really take off, it still needs policy encouragement, the improvement of market mechanisms, and the continuous advancement of technology (Batog et al., 2020; Jiang et al., 2024).

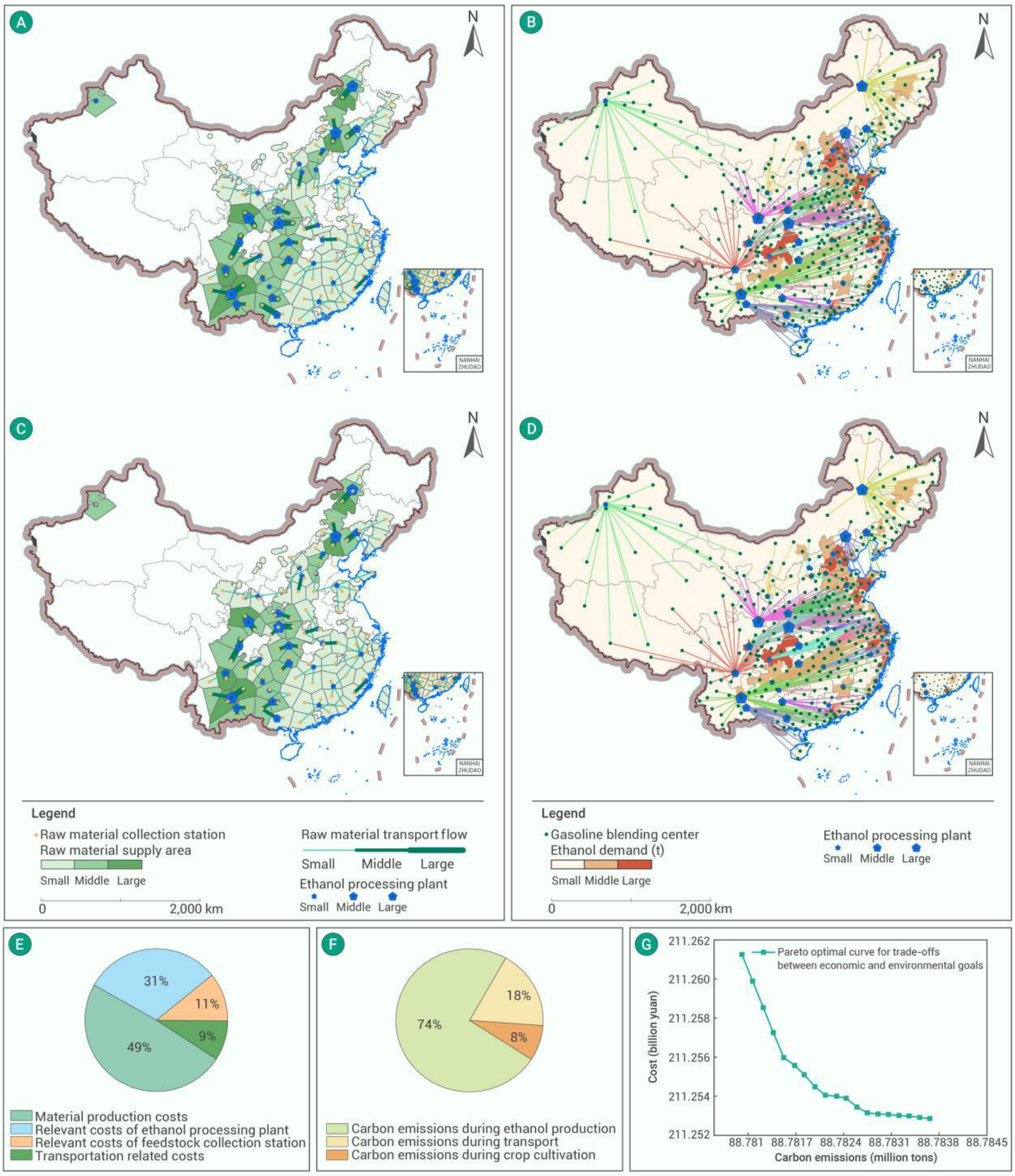

Figure 2 Optimization Layout and Comprehensive Benefits of Sweet Sorghum Ethanol Supply Chain (Adopted from Jiang et al., 2024)

Note: (A) Optimal supply network from raw material collection station to ethanol processing plant under economic optimization. (B) Optimal supply chain from ethanol processing plant to distribution centers under economic optimization. (C) Optimal supply network from raw material collection station to ethanol processing plant under environmental optimization. (D) Optimal supply chain from ethanol processing plant to distribution centers under environmental optimization. (E) Minimum production cost decomposition under economic optimization. (F) Minimum carbon emissions decomposition under environmental optimization. (G) Pareto optimal curve for trade-offs between economic and environmental goals (Adopted from Jiang et al., 2024)

8 Case Study: Pilot or Regional Sorghum-to-Ethanol Projects

8.1 Example project: (e.g., A pilot project in India, China, or U.S. Midwest)

A three-year field pilot was conducted in Fort Valley, Georgia, USA. The main purpose of this trial was to determine whether three sweet sorghum varieties (Dale, M81 E, and Theis) were suitable for ethanol production (Ekefre et al., 2017). The researchers systematically recorded several key points, such as the yield of these sorghum varieties, the amount of juice extracted, the sugar content, and how much ethanol they could theoretically produce.

8.2 Key findings: yield performance, processing efficiency, community impact.

8.2.1 Yield Performance

Of the three varieties, Theis had the highest theoretical ethanol yield, reaching 7 619 liters per hectare, while Dale had the lowest, at 5 077 liters. M81 E had the highest stem dry weight, reaching 27 tons per hectare, while Theis had the lightest stem, at 21 tons. In terms of juice extraction, M81 E produced the most juice, up to 10 915 liters (Ekefre et al., 2017).

8.2.2 Processing efficiency

The sugar content (°Bx) and the amount of sugar that can be extracted from these sorghums vary greatly, which directly affects how much ethanol can be produced. Theis has the highest sugar content, reaching 14.9°Bx, while Dale has the lowest (Ekefre et al., 2017).

8.2.3 Community impact

Sorghum is highly adaptable and requires little fertilizer and pesticide, making it very suitable for promotion as an energy crop. For the local area, such crops can enrich agricultural varieties and help the rural economy develop better (Ekefre et al., 2017; van Rijn et al., 2018).

8.3 Lessons learned: bottlenecks, technical successes, policy support.

From the pilot, the yield and sugar content of different varieties vary greatly, which makes ethanol production unstable. In addition, there is still room for improvement in the current pretreatment and saccharification efficiency (Ekefre et al., 2017; Joy and Krishnan, 2022). By breeding new varieties and adjusting planting methods, sorghum yield and sugar content can be higher. In terms of processing technology, some new methods, such as phosphoric acid catalytic pretreatment and L+SScF process, can also increase sugar and ethanol production (van Rijn et al., 2018; Joy and Krishnan, 2022). This pilot also found that if there is policy support, such as subsidies for ethanol prices and rural development funds, sorghum ethanol can compete with gasoline in price. In this way, it can not only promote renewable energy, but also drive rural development (Prasad et al., 2007; van Rijn et al., 2018).

9 Future Prospects and Research Directions

9.1 Genetic improvements and breeding: high-biomass, low-lignin, high-sugar cultivars.

The most critical step to increase sorghum ethanol production is to improve its genetic characteristics. Studies have found that by digging deeper into the genetic diversity of sorghum, especially using some mutants such as brown midrib (BMR), the lignin content can be greatly reduced (Rivera-Burgos et al., 2019). This makes it easier for cellulose to be broken down into sugars, ultimately increasing ethanol production. Varieties with high sugar content and high yield, such as Sucrosorgo 506, BRS 506 and Theis, have performed well in different regions and under different planting methods, with high ethanol production and biomass (Ekefre et al., 2017; Batog et al., 2020; Ferreira-Neto et al., 2021). In the future, in terms of breeding, the focus should be on selecting varieties that can achieve "high yield, high sugar, and low lignin" at the same time. This not only improves conversion efficiency, but also adapts to more environmental conditions (Ekefre et al., 2017; Rivera-Burgos et al., 2019).

9.2 Integration with biorefineries: co-generation, circular bioeconomy models.

Sorghum can not only be used to make ethanol, but also cooperate with biorefineries to achieve an integrated utilization method. Joy and Krishnan (2022) used crude glycerol, a byproduct of biodiesel, to treat sorghum in their research. This approach can greatly increase the production of sugar and ethanol, and can also better link the ethanol and biodiesel industries. If sorghum is irrigated with treated domestic sewage, its biomass can also be increased, and it can generate electricity and produce ethanol at the same time, thus using wastewater resources and promoting recycling (Ferreira-Neto et al., 2021). In the future, it is necessary to further promote the deep integration of sorghum and biorefineries, develop a more energy-saving, low-carbon and efficient industrial model, and make the entire system more sustainable (van Rijn et al., 2018; Ferreira-Neto et al., 2021; Joy and Krishnan, 2022).

9.3 Research gaps: scalability, microbial tolerance, policy models.

Although the effect of sorghum in making ethanol is quite good in laboratories and small trials, there are still many problems in large-scale application. First, the economic benefits and technical details of large-scale production need to be resolved. For example, the price of enzymes, the energy used in pretreatment, and whether by-products can be used, all need further research (van Rijn et al., 2018; Boboescu et al., 2019). Second, the high sugar and inhibitory environment is a challenge for fermentation bacteria. If you want to increase yields, you have to find strains that are more tolerant to these environments, or modify them (Sathesh-Prabu and Murugesan, 2011; van Rijn et al., 2018). Another big problem is the policy level. For example, how to use land, how to ensure food security, and how to balance energy and agricultural development, all of these lack systematic research. Only by considering these socioeconomic issues together can we truly promote the sustainable development of sorghum ethanol (Prasad et al., 2007; van Rijn et al., 2018; Batog et al., 2020).

10 Conclusions

Sorghum biomass has high yield, strong drought resistance, and adaptability to different environments. It is a very promising fuel ethanol feedstock. If the pretreatment method is optimized, such as using organic solvents, alkali or enzymes, the yield of sugar and ethanol can be greatly increased.

Different sorghum varieties and their planting methods (such as as main crops, double crops or planting in marginal land) will affect ethanol production. Some varieties can also have good yields when planted in temperate and marginal plots. Technical and economic analysis shows that if the by-products can be fully utilized, small ethanol plants using sweet sorghum are promising to make money. Planting sorghum straw and marginal land can also reduce competition with food crops and make the whole more sustainable. From a technical and economic point of view, it is reliable to use sorghum for fuel ethanol. As long as the variety is selected and combined with reasonable processing and fermentation technology, the ethanol yield can even be similar to that of sugarcane. In the main crop or double cropping mode, some varieties (such as Sucrosorgo 506, BRS 506, GN-4) can have high yields in temperate and tropical regions.

Economic analysis also found that if the whole sorghum plant and its byproducts are used, the payback time is fast and the rate of return is high. In addition, the use of marginal land and waste can also improve environmental and social sustainability. However, the yield and economic benefits of marginal land are still not as good as those of good land. In this regard, more suitable varieties need to be selected and the technology needs to be improved.

Suggestions for different participants:

For researchers: Continue to improve sorghum varieties, increase sugar content and total yield, reduce lignin, and make sugar easier to extract. Study more energy-saving, cost-saving and efficient processing and fermentation methods. Conduct more field trials to test the performance of different regions and varieties and find the most stable combination.

For policymakers: Introduce policies to encourage the planting of non-grain energy crops such as sorghum, especially to support multiple cropping and the use of marginal land. Promote the development and utilization of byproducts and the construction of the entire industrial chain. It is also necessary to increase financial support to reduce the risk of initial investment by enterprises.

For enterprises: Consider investing in sorghum ethanol projects, give priority to high-yield and adaptable varieties, and adopt efficient pretreatment technologies. By-products should not be wasted. For example, they can be used as pellet fuel, feed or food to further increase profits. At the same time, we should cooperate with farmers and scientific research institutions to establish a stable supply chain of raw materials and technologies.

For farmers: Choose sorghum varieties suitable for local climate and soil, and reasonably arrange main crops and repeated crops to make land use more efficient. Participating in the sorghum supply chain can not only sell grain, but also earn more income through straw and by-products. Pay more attention to the promotion of new technologies and new varieties, which can increase production and be more resistant to risks.

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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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