Zhang *et al.*
*Biotechnology for Biofuels and Bioproducts (2024) 17:134*
https://doi.org/10.1186/s13068-024-02582-6

Biotechnology for Biofuels and Bioproducts

RESEARCH

Open Access

# Potential, economic and ecological benefits of sweet sorghum bio-industry in China

Ru Zhang[1,2†], Gang Lin[3†], Li Shang[1], Xiaoyuan Wu[1], Zhiquan Liu[1], Longchao Xu[1], Qinglin Sun[1], Jingying Fu[3*], Huaiqing Hao[1*] and Hai-Chun Jing[1,2,4]

## Abstract

**Background** Sweet sorghum (*Sorghum bicolor*) displays an excellent potential to serve as a non-food bioenergy feedstock for bioethanol production in China due to its high potential yield on marginal lands. However, few studies have been conducted on the potential of sweet sorghum yield and appropriate industrial models in different marginal regions in China. This study explored the spatial distribution of potential sweet sorghum production using the Decision Support System for Agrotechnology Transfer (DSSAT) model and proposed three typical industrial models of sweet sorghum industry to calculate their economic and ecological benefits.

**Results** The results indicate that considering the factors of land use, annual precipitation, soil salinity, soil pH, and accumulated temperature, approximately 32.23 million ha of marginal land are suitable for sweet sorghum cultivation in China, and 130 million tonnes (t) of ethanol can be produced. Further, the development of the sweet sorghum industry under the three models can generate 1425.49 billion CNY potential, approximately accounting for 3.57% of industrial added value in China if measured against 2023 levels, and reduce $CO_2$ emissions by 4.68 million t.

**Conclusions** This study provides an innovative perspective for the multi-industry large-scale promotion of sweet sorghum in different marginal lands based on the high spatial resolution Geographic Information System (GIS) data by the DSSAT model with a Life Cycle Assessment (LCA) method, and this applies not only to China but also to the worldwide and other types of energy plants.

**Keywords** Sweet sorghum, Industrial models, Decision Support System for Agrotechnology Transfer (DSSAT), Life Cycle Assessment (LCA), Marginal lands, Carbon reduction

## Background

Sweet sorghum (*Sorghum bicolor*) is a $C_4$ graminaceous crop with high biomass production, high stem sugar content, and distinctive tolerance to adverse conditions [1–3]. Such advantageous features combined with the property of 'dual-sink' of grain and stem harvests make sweet sorghum widely explored for multiple industrial uses as food, feed, fuel, liquor, and forage [4–6], and hence, such multi-functionality allows for the development of industrial pipelines integrating bioethanol production with crop and livestock farming as well as fine chemicals production. At the beginning of the twentieth century, the sweet sorghum bio-industry attracted much

†Ru Zhang and Gang Lin contributed equally to the work.

*Correspondence:
Jingying Fu
fujy@igsnrr.ac.cn
Huaiqing Hao
hqhao@ibcas.ac.cn
[1] Key Laboratory of Plant Resources, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[4] Engineering Laboratory for Grass-Based Livestock Husbandry, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China

interest globally, especially in the United States, Brazil, Australia, India, and China, and significant achievements have been made in sweet sorghum breeding, cultivation, and processing techniques [1, 7].

China has a long history of sorghum cultivation, dating back to 4000–5000 years ago, and sorghum grains used to be one of the staple foods in North China until the 1930s [8]. However, with the introduction of high-yielding and high-quality varieties of maize (*Zea mays*) and wheat (*Triticum aestivum*), plus the cheaper supplies from the international market, the role of sorghum grains as food has been replaced and the production of grain sorghum has gradually reduced [9]. Since 1995, the proportion of sorghum planting in China has declined year by year, and then increased after falling to the lowest level (0.25%) in 2015 [10]. Currently, sorghum production is primarily driven by the liquor industry in China, and in 2020, the total sowing area of sorghum is 6,364,506 ha, accounting for 0.38% of the total crop sowing areas [7, 10]. One of the lessons learned from the liquor industry is that both grain and sweet sorghum could be produced by a crop under the low input system on the majority of marginal land in China, which is primarily located from northeast to southwest China. Moreover, China's large population (1.4 billion) has increasingly limited arable land per capita [11], which is discouraged for biofuel development [12]. Using marginal land to develop bioenergy crops can not only bring economic benefits, but also avoid negative competition with food production [13, 14]. China possesses approximately 134 million ha of marginal land resources, including wasteland, saline-alkali land and low fertility land, and around 49.65 million ha of marginal land in China is suitable for sweet sorghum cultivation [15, 16]. Because of this, China is becoming one of the leading countries in developing sweet sorghum bio-industries on marginal land [17].

To obtain the maximum benefits, it is necessary to judge which sweet sorghum bio-industry and sweet sorghum characteristics are suitable for development in different regions. Despite high expectations over the past decades, few successful industry-scale paradigms have been witnessed so far. This is largely because current biofuel projects only focus on a single product of energy plants or only consider bioethanol and by-product dried distillers grains with solubles (DDGS) (Supplemental Data Set S1) [5, 6, 15, 18–21]. Few projects are tailored to local conditions with holistic consideration of agricultural production, land utilization, multiple end products, and so on, resulting in resources waste, low economic benefits, and even environmental pollution. It is necessary to consider the comprehensive development models of biofuels in different regions from the perspective of sustainable development. Thus, in the present study, we (1) explore the spatial distribution of the potential of sweet sorghum yield using the Decision Support System for Agrotechnology Transfer (DSSAT) model; (2) evaluate the current distribution of the sweet sorghum bio-industry in various eco-regions; and (3) estimate the economic and ecological potentials for three typical sweet sorghum industry, and discuss the bioenergy-related traits improvement for sweet sorghum. This article provides a spatial view of sweet sorghum production in China, proposes suitable sweet sorghum industrial models in different ecological zones and evaluates their economic and ecological benefits by combining LCA and DSSAT models, which will be helpful to decision-making for the development of the sweet sorghum bio-industry.

## Methods

### Model for the potential of sweet sorghum yield estimation

The DSSAT model, which combines soil, weather, crop management and experimental data, is one of the widely used crop models in the field of assessing the impact of climate change on crop growth and development and crop management measures. The latest version (v4.8.2) has provided 42 crop simulation models [22–24]. In our study, it is used to estimate sweet sorghum yield in this study with terrain, climate, soil and management datasets from the field, and the marginal land is a limiting condition to control the simulation scope in the model.

According to the definition from the Ministry of Agriculture of China, marginal land refers to winter fallow paddy fields and wasteland that can be used to grow energy crops. Wasteland includes shrub land, sparse forest land, grassland, shoal/bottomland, and unused land [25]. Grassland is excluded due to the policy of returning farmland to grassland and the consideration of not competing with animal husbandry. Further, environmentally sensitive lands like nature reserves are excluded. Based on the land use, precipitation, soil, and air temperature data, the growing conditions required for sweet sorghum are listed in Table 1. The marginal land suitable for sweet sorghum growth is extracted using a multifactor integrated assessment method according to different growing conditions [26].

Nationwide geographic and statistical data from 2000 to 2020 are utilized in this study to assess the potential suitable land for sweet sorghum production. Geographic data included those for marginal land extraction and sweet sorghum yield estimation by the DSSAT model. All geographic data are presented in Table 2. Statistical data consisted of datasets for the DSSAT model, such as field management data and crop species parameters [30–32].

**Table 1** Growing conditions required for sweet sorghum

| Factors | Specific parameters | Threshold | References |
|---|---|---|---|
| Land use | Land use type | Shrub land, sparse forest land, shoal/bottomland, alkaline land and bare land | [25] |
| | Nature reserve | Excluding nature reserve | |
| Precipitation | Annual precipitation/mm | ≥ 300 | [27] |
| Soil | Salinity/% | < 0.6% | [28] |
| | pH ($H_2O$) | 5.0–8.5 | [29] |
| Temperature | ≥ 10 °C accumulated temperature/°C | ≥ 1500 | [29] |

**Table 2** Basic geographic and statistical data

| Factors | Factors | Specific description | Resolution (km) | Data sources |
|---|---|---|---|---|
| Geographic data | Land use | | 1 | Data Center for Resources and Environmental Sciences (RESDC) [15, 27] |
| | Climate | Raster data for marginal land extraction | 1 | RESDC [15, 27] |
| | | Site data for the DSSAT model | – | China Meteorological Administration (CMA) [15, 27] |
| | Soil | Salinity and pH ($H_2O$) for marginal land extraction | 1 | RESDC [15, 27] |
| | | Soil profiles for the DSSAT model | 1 | Cold and Arid Regions Science Data Center (CARD) [15, 27] |
| Statistical data | Field management data | Required by the DSSAT model | – | Field experiment records |
| | Crop species parameters | Required by the DSSAT model | – | Literature [30–32] |

### Model for the input–output analysis of sweet sorghum industry

Early on, Life Cycle Assessments (LCA), based on the bottom to-top method, is successfully applied to evaluate the potential environmental impacts and economic efficiency for a production and process system in the whole life cycle [18]. Generally, there are four phases for one production in that cycle: (1) production (including the utilization of the raw material), (2) sales/transportation, (3) service and (4) final treatment. Each stage may cause differing cost input. In this study, LCA method is used to evaluate the economic benefit of the sweet sorghum industrial models in China. Detailed inventory and the input–output analysis are summarized in the Supplemental Data Set S2–S6.

### Method of ecological benefit assessment

In this study, carbon emission is analyzed based on the principle of carbon balance. That is, carbon is absorbed from the atmosphere during the sweet sorghum planting stage and returned to the atmosphere through the bioethanol combustion stage. However, in fact, extra carbon like fertilizers, fossil fuels, etc., is required to maintain the progress of bio-ethanol throughout its life cycle. This extra carbon is the main source of carbon emissions. We divide the life cycle of sweet sorghum-based ethanol into four stages, sweet sorghum planting stage, sweet sorghum transportation stage, ethanol production stage and transportation stage. The carbon released in the sweet sorghum planting stage includes fertilizers, herbicides, insecticides, and diesel oil in agricultural machinery. The carbon emissions of sweet sorghum transportation and bioethanol transportation are mainly electricity and diesel consumption. The carbon emissions from the bioethanol production stage are calculated from the input of electricity, steam, coal, and subtract the carbon emissions reduced by byproducts (solid granular fuel produced during ethanol production) [19, 33]. The sum of carbon emissions from the four stages is the total carbon emissions. The formula is as follows [19, 33]:

$$C_{\mathrm{emission}} = \sum Ci = C1 + C2 + C3 + C4,$$

where $C_{emission}$ (unit: t $CO_2$) is the total carbon emissions over the life cycle of sweet sorghum-based ethanol; $Ci$ is the carbon emission of stage $i$. $C_1$ is the carbon emission of sweet sorghum planting stage; $C_2$ is the carbon emission of sweet sorghum transport stage; $C_3$ is the carbon emission of bio-ethanol production stage; $C_4$ is the carbon emission of ethanol transport stage (see Supplemental Data Set S7 for details).

The estimate of carbon reduction mainly considers the carbon emission reduction of biofuel ethanol compared with petroleum at the same energy output. The formula for crop carbon reduction is as follows [19, 33–35]:

$$C_{\text{reduce}} = \frac{Y \times BE \times W}{E \times 1000},$$

where $C_{\text{reduce}}$ (unit: t $CO_2$) is the carbon reduction of biofuel ethanol compared with petroleum at the same energy output; $Y$ (unit: t) is sweet sorghum biomass yield; $E$ is the conversion coefficient of sorghum biomass to ethanol (16:1); BE is the output energy of ethanol combustion (29,660 MJ/t ethanol); W is the conversion factor of calorific value to petroleum (0.0189 t $CO_2$/MJ) [19, 33–35]. The ecological benefits are net carbon reduction, that is, the carbon reduction minus the carbon emission value.

## Results

### Spatial distribution of sweet sorghum yield

An estimate of the sweet sorghum yield is conducted within the scope of the marginal land suitable for its planting using the DSSAT model. According to the ratio of sweet sorghum stalk to grain 20:1, the sweet sorghum biomass yield simulated by the model is converted to stalk yield. The bioethanol production is estimated by dividing sweet sorghum stalk yield by 16 (the conversion coefficient of sweet sorghum stalk: ethanol 16:1) [34, 35]. Land use, annual precipitation, soil salinity, soil pH, and ≥10 °C accumulated temperature are considered in sweet sorghum growth conditions (Fig. 1).

Based on the results, the sweet sorghum planting area, sweet sorghum stalk yield and total output of sweet sorghum stalks, as well as ethanol production are calculated (Table 3). The marginal land area of sweet sorghum can be planted on approximately 32.23 million hectares, and the theoretical sweet sorghum stalk production is more than 2 gigatonne (Gt), converting into 130 million tonnes (t) of bioethanol (Table 3).

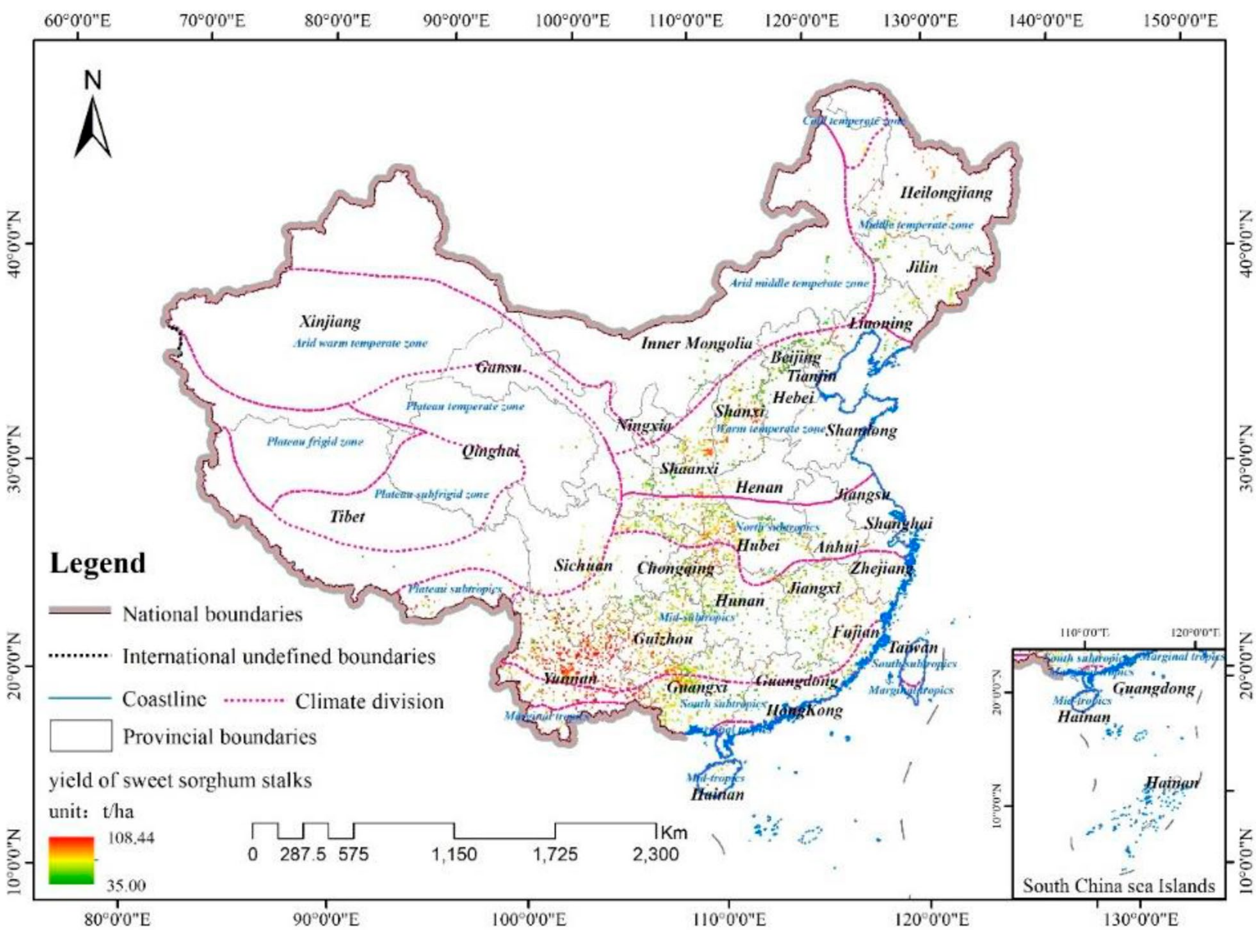


**Fig. 1** Spatial distribution of sweet sorghum annual production in China

**Table 3** The statistical data of sweet sorghum planting

| Area ($10^6$ ha) | Yield of sweet sorghum stalks (t/ha*yr) | Total output of sweet sorghum stalks ($10^8$ t/yr) | Fuel ethanol production ($10^8$ t/yr) |
|---|---|---|---|
| 32.23 | 35.00–108.44 | 20.88 | 1.30 |

### Priorities of sweet sorghum industrial model in various eco-regions in China

Table 4 shows the environmental conditions for the sweet sorghum growth in various eco-regions divided by climate zone. Based on the spatial cluster of sweet sorghum, three typical industrial models of sweet sorghum, namely, the industrial model in the arid and semi-arid North, the year-round cultivation and harvest model in Southwest Karst landscape, and the high value driving development model in coastal regions, which are established by considering the climate characteristics, cropping systems, and potential and cultivation practice in various eco-regions. For example, the plateau frigid zone and plateau sub-frigid zone have neither land suitable for sweet sorghum growing nor sweet sorghum bio-industries, which are not suitable for developing sweet sorghum industry. In warm temperate zone, the feed industry is the best match for output of sweet sorghum, and sugar and alcohol enterprises also match well, so it is suitable to prioritize the development of feed, while also encouraging the development of sugar and alcohol.

### Model 1: the sweet sorghum industrial model in the arid and semi-arid North China

There are abundant marginal land resources in arid and semi-arid Northern China, mainly distributed in cold temperate zone, arid middle temperate zone and middle temperate zone (Fig. 1; Table 4). In 2016, NEA made an ambitious call to establish new bioethanol production lines in North China provinces. Different from previous bioethanol projects which solely used maize kernel as the material, a compulsory requirement was to include no less than 100,000 t/yr bioethanol from sweet sorghum feedstock, in addition to using "aged grains" and crop straws [36]. Based on this proposal, a so-called two-step distributed processing design is proposed (Fig. 2A). The first step focused on juice crushing and concentrating. Six satellite production units (unit 1–6) of 10,000 ha are designated, each integrating sweet sorghum cultivation and sheltered livestock farming to form a circular agro-business. Within such a circular unit, a sweet sorghum juice crushing and condensing factory with a processing capacity of 5000–20,000 t/dy of fresh stems is designed, and syrups of 45% Brix are produced as the final product. Meanwhile, the bagasse (fibrous residue after crushing) and leaves are processed for the livestock, which in turn can produce manures and organic fertilizers for sweet sorghum cultivation. In the second step, a large-scale centralized ethanol conversion and refinery plant can be built to process the syrups delivered in batches. The

**Table 4** The environmental conditions for the sweet sorghum growth in various eco-regions

| Climatic zone | Annual precipitation/mm | Salinity/% | pH ($H_2O$) | ≥ 10 °C accumulated temperature/°C | Frost-free period/d | Cropping system |
|---|---|---|---|---|---|---|
| North subtropics | 526.2–1721.0 | 0–0.12 | 5.0–8.4 | 1941.9–5684.9 | 190.8–305.6 | Single-harvest, double-harvest, and triple-harvest |
| Marginal tropics | 1152.4–1881.0 | 0–0.29 | 5.0–7.9 | 4282.2–8622.5 | 352.2–365.0 | Double-harvest and triple-harvest |
| Arid warm temperate zone | 356.1–384.2 | 0–0.02 | 6.4–8 | 2297.2–2606.3 | 171.6–173.2 | Single-harvest |
| Arid middle temperate zone | 306.6–513.6 | 0–0.18 | 5.7–8.4 | 1515.8–3365.1 | 115.8–176.6 | Single-harvest |
| Plateau temperate zone | 301.3–1604.9 | 0–0.1 | 5.1–8.2 | 1500.0–4271.2 | 109.0–272.0 | Single-harvest and double-harvest |
| Plateau subtropics | 349.3–827.2 | 0–0.02 | 5.0–8.0 | 1500.0–8579.0 | 146.0–214.8 | Single-harvest |
| Cold temperate zone | 488.5–525.9 | 0–0.01 | 6.1–7.8 | 1518.9–1859.6 | 106.1–113.1 | Single-harvest |
| South subtropics | 797.6–2102.9 | 0–0.05 | 5.0–8.3 | 2273.9–8103.2 | 320.3–365.0 | Double-harvest and triple-harvest |
| Warm temperate zone | 363.1–943.2 | 0–0.27 | 5.1–8.4 | 1500.0–4465.6 | 151.6–244.0 | Single-harvest and double-harvest |
| Mid-tropics | 1263.4–2080.8 | 0–0.005 | 5.0–6.6 | 8467.4–9193.3 | 365.0 | Triple-harvest |
| Middle temperate zone | 416.1–1143.9 | 0–0.18 | 5.0–8.4 | 1552.6–3068.5 | 105.6–182.3 | Single-harvest |
| Mid-subtropics | 361.2–2056.7 | 0–0.44 | 5.0–8.4 | 1500.0–7517.4 | 194.3–353.8 | Single-harvest, double-harvest, and triple-harvest |

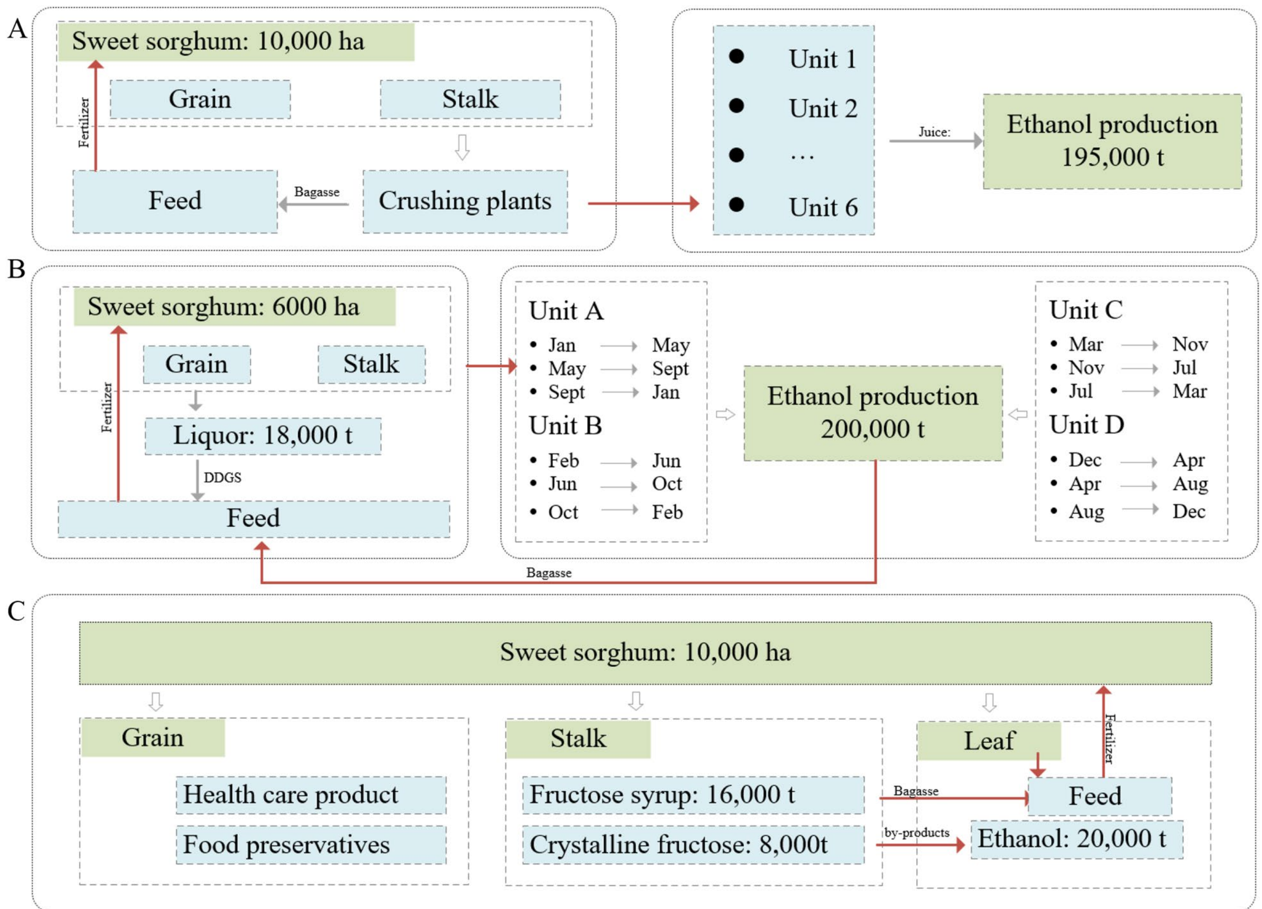


**Fig. 2** The system boundary and the input–output for three models

Supplemental Data Set S2–S4 shows the required inputs and the corresponding outputs in this model, which are expected to achieve production of 195,000 t/yr ethanol (Fig. 2A). Based on this model, the first few production lines in Inner Mongolia and Jilin province are under evaluation and implementation.

#### Model 2: the sweet sorghum year-round cultivation and harvest model in Southwest regions

The Southwestern region of China mainly includes marginal tropics, south subtropics, mid-tropics and mid-subtropics (Table 4). These regions are warm and humid all year round and the favorable climatic conditions can get three or four crops in a year, realizing the continuous supply of feedstocks. A year-round cultivation and harvest model are developed (Fig. 2B). In this production model, four independent cultivation units, each of 6000 ha, are proposed to ensure 12 months of continuous harvesting and supply of fresh stems for ethanol production. For example, in Unit A, sweet sorghum can be planted in January, May, and September, while the harvesting can take place in May, September, and January. As shown in Fig. 2B, this model can produce a total of 200,000 t/yr ethanol (see Supplemental Data Set S3 for details). In southwest China, there are many famous liquor enterprises, such as the Moutai and Wuliangye. The liquor industry can drive the development of the other sorghum bio-industries in the region. The sorghum grains supplied to liquor enterprises, can produce 72,000 t of liquor (Supplemental Data Set S3). The bagasse after stem crushing and DDGS (dried distillers' grains with solubles) can be returned to farmers and mixed with other forage grass to feed goats, and the manure can be used for fertilization [37]. In addition, because of the karst mountains, this region is not conducive to large-scale production, and the cooperation between farmers and enterprises is adopted to drive farmers out of poverty and enable enterprises to obtain higher profits [26, 38, 39].

### Model 3: the sweet sorghum high value driving development model in coastal regions

Model 3 is witnessed in coastal regions (mainly in warm temperate zone and Guangdong Province). Depending on the superior environmental and social conditions, as well as technological research and development conditions in coastal regions, it is possible to focus on the high value-added industry driving development model (Fig. 2C). More than 10,000 ha of sweet sorghum are expected to be planted, fructose syrup or crystalline fructose can be extracted from the stem juice rich in sugar, the bagasse can be made into ruminant roughage, and the by-products produced in fructose production can be converted into bioethanol. These grains can also be used to develop health care products and food preservatives. As coastal areas cover a wide range of regions, it is possible to learn from the first two models to achieve a continuous supply of feedstocks according to local climatic conditions. A successful example is the Beimingshi Technology Development Co., Ltd. in Guangdong province, which has obtained a patent for its sweet sorghum fructose and ethanol integrated utilization industrial project. Based on the company's production data, we estimated that 24,000 t/yr of fructose and 20,000 t/yr of ethanol can be produced per 10,000 ha of sweet sorghum in the industrial model (Fig. 2C; Supplemental Data Set 3).

(A) Model 1: the sweet sorghum industrial model in the arid and semi-arid North China

Six 10,000 ha satellite production units (unit 1–6) are designated, each with bagasse available for feed, which in turn can provide fertilizer for sweet sorghum cultivation. The stalk juice from six units delivered in batches can produce 195,000 t/yr ethanol.

(B) Model 2: the sweet sorghum year-round cultivation and harvest model in Southwest regions

Four independent units (unit A–D) each plant 6000 ha of sweet sorghum to ensure 12 months of continuous supply of fresh stems for ethanol production and can produce 200,000 t/yr of ethanol. Grains from each unit can produce 18,000 t/yr baijiu, and the bagasse and DDGS are returned to farmers to feed.

(C) Model 3: the sweet sorghum high value driving development model in coastal regions

The stalk juice from 10,000 ha of sweet sorghum can extract 24,000 t/yr fructose, and the bagasse and sorghum leaf can be made into ruminant roughage, and the by-products produced in fructose production can be converted into 20,000 t/yr bioethanol. The grain can be used for health care product, etc.

**Table 5** The stalk of sweet sorghum planting for Models 1–3

| Models | Area ($10^6$ ha) | Yield of sweet sorghum stalks ($10^8$ t/yr) |
|---|---|---|
| Model 1 | 2.60 | 1.54 |
| Model 2 | 19.03 | 12.95 |
| Model 3 | 5.34 | 3.10 |

**Table 6** The economic benefit of sweet sorghum industry for different models in China (unit: billion CNY/yr)

| Model 1 | Model 2 | Model 3 | Total |
|---|---|---|---|
| 33.58 | 1279.52 | 112.39 | 1425.49 |

### The economic and ecological benefit analysis of sweet sorghum industry under three models

Table 5 shows the stalk of sweet sorghum planting for different models. Based on the climate conditions, it is pointed out that Model 2 is simple and practicable and is favorable for wide-range popularization and development. The yield of sweet sorghum stalks of Model 2 is 1.30 Gt/yr. The yield of sweet sorghum stalks of Models 1 and 3 are relatively small, both less than 40% of that of Model 2.

According to the calculation for the input–output analysis of sweet sorghum industry, the unit profit per hectare of sweet sorghum for Models 1–3 are approximately 12,916.10 CNY/ha*yr, 67,236.92 CNY/ha*yr and 21,046.12 CNY/ha*yr, respectively (see Supplemental Data Set S4–S6 for details). Next, the total economic benefit of sweet sorghum industry for Models 1–3 are estimated by multiplying the suitable planting area of sweet sorghum by the unit profit based on the sweet sorghum scale in this study. Table 6 shows the economic benefit of sweet sorghum industry for different Models in China, which is estimated by the total cost input and output throughout the whole life cycle. In Model 2, there is not only a large scale of production, but also a high level of economic benefit, with the economic benefit of approximately 1279.52 billion CNY/yr (Tables 5 and 6). The economic benefit of Model 3 is approximately 112.39 billion CNY/yr, while that of Model 1 is approximately 33.58 billion CNY/yr (Table 6). That is to say, there is about 1425.49 billion CNY/yr potential can be generated by developing the sweet sorghum industry, approximately accounting for 3.57% of industrial added value in China if measured against 2023 levels [40].

In addition to economic benefits, the ecological benefits are also assessed. The Chinese government has put forward a national strategic goal of achieving carbon-peak by 2030 and carbon-neutral by 2060 [12]. Sweet sorghum has important carbon reduction potential, and its ecological advantage is more significant on marginal land. Therefore, the carbon emission and carbon reduction are calculated under these three models. The results showed that the net carbon reduction is positive for all three models, with a total net reduction of 4.68 million t/yr of $CO_2$ (Table 7), indicating that the sweet sorghum industry models proposed have great ecological benefits. Detailed analysis is summarized in Supplemental Data Set S7.

## Discussion

In China, due to the scarcity of arable land resources, marginal land can be used as the most important strategic emergency resource [41]. Sweet sorghum, which is characterized by high yield, ease of extractability, strong stress tolerance and low input requirements, can be widely grown on marginal land and produce good benefits [3, 6, 42]. In the present study, we analyzed the potential of sweet sorghum on marginal land and found that sweet sorghum industrial development can bring significant economic and ecological benefits. Our study provides a reference for the large-scale promotion of sweet sorghum industry and comprehensive utilization of sweet sorghum and also provides an innovative perspective for the development of sweet sorghum industry in different marginal land in China.

1. Comparison with other studies

   We compared this study with other studies in terms of suitable spatial distribution of feedstock, yield, and ethanol production potential and industry benefits.

   Considering land use, annual precipitation, soil salinity, soil pH, accumulated temperature, the suitable marginal land area is 32.23 million ha, the yield of sweet sorghum stalk is 2.09 Gt, which can be converted into ethanol 130 million t (Table 3). Jiang et al.'s research showed that about 49.65 million hectares of marginal land in China are suitable for growing sweet sorghum [15]. Hao et al. considered the water supply and demand relationship during the growth of sweet sorghum, and concluded that the area suitable for the development of sweet sorghum fuel ethanol was 31.18 million ha, which only accounts for 77% of the original marginal land [43]. The reason for the difference in these results is that the models used to simulate the spatial distribution are different, and the environmental constraints considered are different. The study by Fu et al. showed that the potential production of bioethanol from 2020 to 2030 was estimated at 145.42 million t considering different feedstocks [27]. Zhuang et al. found that the marginal land area suitable for energy plants was about 43.75 million ha, and biofuel production could reach 133.85 million t [35]. These estimated ethanol potential data are basically consistent with our research data, which verifies the reliability of the data in this article.

**Table 7** The ecological benefit of sweet sorghum industrial for different models in China (unit: million t/yr $CO_2$)

| Models | Carbon emission | Carbon reduction | Net carbon reduction |
|---|---|---|---|
| Model 1 | 5.02 | 5.40 | 0.38 |
| Model 2 | 41.80 | 45.37 | 3.57 |
| Model 3 | 10.12 | 10.86 | 0.74 |

Our research shows that the sweet sorghum industrial model adapted to marginal land development in different ecological regions can obtain positive economic and ecological benefits (Tables 6 and 7). The previous study on the $CO_2$ emission reduction potential of saline-alkali land in Dongying City was 63,900 t [19]. Ding et al. found that compared with gasoline, ethanol based on sweet sorghum stalk had advantages in energy consumption, which could reduce fossil energy by 85% and global warming potential by 44% [18]. Research conducted by Jiang et al. indicated that Guizhou Province can give priority to the development of sweet sorghum bioethanol [15]. Our results also show that the economic and ecological benefits of sweet sorghum industry with Model 2 (including Guizhou Province) are the highest. The economic benefit of sweet sorghum bioenergy production in Inner Mongolia was negative in ref [20], but the estimated benefit of Model 1 (including Inner Mongolia Province) in our research is positive, because we assume full use of the versatility of sweet sorghum, integrate different industries, and then produce large economic benefits.

In terms of carbon accounting of fuel ethanol, in order to facilitate calculation, some researches regard fuel ethanol as a carbon-neutral energy, that is, the absorption and emission of $CO_2$ by fuel ethanol in the process of raw material production, processing and conversion and fuel use reach a dynamic balance [44]. At present, there is no clear conclusion on the life cycle carbon emissions of various raw materials [44]. We consider that carbon emissions of fuel ethanol should not be ignored. Therefore, this study fully considers carbon emission and carbon emission reduction of fuel ethanol [19, 33]. The carbon emission is analyzed according to the principle of carbon balance. The sum of carbon emissions from the four stages of sweet sorghum planting stage, sweet sorghum transportation stage, ethanol production stage and transportation stage is the total carbon emissions of fuel ethanol. The carbon emission reduction calculated in Li et al.'s study was overestimated [44]. Because the carbon emission reduction coefficient only considers the carbon emission reduction of petroleum, while ignoring the carbon released by the combustion of bio-ethanol itself. Therefore, we take into account the carbon emission reduction of biofuel ethanol relative to petroleum at the same energy output in our calculations.

2. Research uncertainties and limitations

   It is worth noting that there are several uncertainties in this study. Although we took into account the yield difference of sweet sorghum in different ecological lands and estimated yields in combination with experimental data, we did not screen and evaluate sorghum varieties in different regions to recommend the most suitable sorghum varieties for different regions.

   In addition, the yield of sorghum bioethanol is affected by the sugar content in the stems, which is closely related to the variety and environment. The sweet sorghum: ethanol conversion coefficient used in this study is a specific value that is not suitable for all sweet sorghum varieties.

   In this study, based on the LCA method, we evaluated the economic benefits of three sweet sorghum industry models in detail. However, the data are based on literature surveys, rather than the actual experimental data, further research is needed before large-scale production. In the calculation of ecological benefits, although our calculation method has been improved compared with predecessors, it still cannot reach the actual situation. In addition to bioethanol, the output of sweet sorghum in our study also includes feed, liquor and syrup, etc. Due to the lack of data on carbon emissions from these outputs, we only considered the ecological benefits from the conversion of all sorghum to ethanol, and not the ecological benefits from other outputs in order to facilitate calculation. With the deepening of the research, more accurate ecological benefit evaluation will be obtained.

3. Improvements through crop varieties and field management practices

   The output of sweet sorghum could be increased by improving the performance of crop varieties due to the great potential of genetic improvement [30]. Excellent sweet sorghum varieties are expected to have larger biomass, better digestibility (lower lignin content), higher sugar content, stronger stress tolerance, etc. [4, 45]. Tailoring sweet sorghum varieties in different environments is a key consideration in the development of the sorghum industry. For Model 1, sorghum should be designed with higher drought tolerance due to the little precipitation during the growing season [20]. And the sorghums are used for ethanol production and silage preparation after harvesting, which requires higher biomass, stem sugar content, and better forage quality. For Model 2, we assume that the sorghum can be harvested year-round due to the favorable climatic conditions, which takes challenges for soil nutrients and crop growth cycle. In addition to ethanol and feed, liquor is also an important output of Model 2, which requires higher grain yield and quality. For Model 3, sorghums can be harvested double or triple in a year in southern coastal regions. In addition to ensuring the high sorghum stem sugar content, forage quality and biomass, improved salt tolerance of sorghum is necessary, as high salinity is harmful to common sorghum varieties growth [46].

   In addition to cultivating high-performing and stable varieties for different ecological regions, the development of sweet sorghum industry could also make full use of local climate and environmental characteristics to reduce the adverse impact on yield on marginal land and maximize economic and ecological benefits. For instance, in Model 1, due to short growing season and low accumulative temperature, sweet sorghum can only grow for one season in these areas, sowing in late April or early May and harvesting in late September or early October. Often, the temperature would drop rapidly to below freezing and reach at least $-15$ °C to $-20$ °C, and hence the narrow growth-harvest window is the biggest constraint for the development of an economically sound industrial model. Interestingly, albeit restricting continuous growth and cultivation of sweet sorghum, the harsh and freezing winter could be taken advantage of and used as "natural cold storage house", which could allow the harvesting and processing to continue for 3 to 6 months during the winter time. Our recent small-scale experiments indicate that it is possible to leave the sweet sorghum stands in the field until early next year and the stem Brix could remain above 11% (unpublished data).

   In the future, combined with the cultivation of super varieties, efficient field management practices, and policy support, the benefits of sweet sorghum industry could be further improved in marginal land [47, 48]. Although sweet sorghum is a promising bioenergy feedstock, it is not the only one, such as sugarcane (*Saccharum officinarum*), jatropha *(Jatropha curcas*), cassava (*Manihot esculenta*), which also have high biofuel development potential on marginal land [25, 35]. The most suitable bioenergy in various regions should be further studied. The industrial model of multi-industry combined development in different ecological areas proposed by us is expected to provide reference for the development of other energy crops.

## Conclusions

This paper simulates the spatial distribution and industrial models of the potential for sweet sorghum production using the method that coupled the DSSAT model with an LCA method and estimated the economic and ecological potential for sweet sorghum industry. The following main conclusions are reached:

(1) The marginal land suitable for sweet sorghum planting in China is approximately 32.23 million ha when considering land use, annual precipitation, soil salinity, soil pH, accumulated temperature. The sweet sorghum stalks can reach an annual maximum production of 108.44 t/ha, and 130 million t of ethanol can be produced in the country.

(2) Three typical industrial models of sweet sorghum are determined to be extended to various ecoregions in this study by considering the climate characteristics, potential and production practice. The unit profit of sweet sorghum for Models 1–3 are approximately 12,916.10 CNY/ha*yr, 67,236.92 CNY/ha*yr and 21,046.12 CNY/ha*yr, respectively.

(3) The annual average economic potential of developing sweet sorghum industry under Models 1–3 can reach 33.58 billion CNY, 1279.52 billion CNY and 112.39 billion CNY, respectively. The ecological benefits are also obvious, with a total $CO_2$ reduction of 4.68 million t per year through the development of three sweet sorghum industry models. Combined with the genetic improvement for key traits, the industrial development potential can be further improved.

In conclusion, this study provides a perspective for the development of the sweet sorghum industry based on high spatial resolution GIS data by the DSSAT model with an LCA method, and this applies not only to China, but also to other regions and other energy plants.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13068-024-02582-6.

Supplementary Material 1.

**Acknowledgements**
Not applicable.

**Author contributions**
All authors planned and supervised the research. HCJ initiated the project. HQH and JYF organized and coordinated the project. RZ and GL designed the database structure. RZ, GL, ZQL and LCX participated in data analysis. RZ drafted the manuscript. HCJ, HQH, LS, XYW, and QLS revised the manuscript. All authors read and approved the final manuscript.

**Funding**
This work was supported by grants from Shandong Province Key Research and Development Program (2021SFGC0303), National Key Research and Development Plan of China (2022YFF1003200), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA26050101) and the National Natural Science Foundation of China (32241041 and 32072026).

**Availability of data and materials**
All datasets are available as Supplemental Data Sets: Set S1. Biofuel ethanol projects under implementation or planning in China. Set S2. Summary of detailed unit costs for different outputs in the sweet sorghum bio-industry; Set S3. Summary of land and output of sweet sorghum industrial for different Models; Set S4–S6. The detail calculation for the input–output analysis of sweet sorghum industrial Models 1, 2, and 3 separately; Set S7. The calculation of net carbon sink of sweet sorghum industry for different models.

## Declarations

**Ethics approval and consent to participate**
Not applicable.

**Consent for publication**
Not applicable.

**Competing interests**
The authors declare no competing interests.

Received: 11 October 2023 Accepted: 31 October 2024
Published online: 08 November 2024

**References**

1. Appiah-Nkansah NB, Li J, Rooney W, Wang D. A review of sweet sorghum as a viable renewable bioenergy crop and its techno-economic analysis. Renew Energy. 2019;143:1121–32.
2. Brenton ZW, Cooper EA, Myers MT, Boyles RE, Shakoor N, Zielinski KJ, Rauh BL, Bridges WC, Morris GP, Kresovich S. A genomic resource for the development, improvement, and exploitation of sorghum for bioenergy. Genetics. 2016;204:21–33.
3. Calviño M, Messing J. Sweet sorghum as a model system for bioenergy crops. Curr Opin Biotechnol. 2012;23:323–9.
4. Hao H, Li Z, Leng C, Lu C, Luo H, Liu Y, Wu X, Liu Z, Shang L, Jing HC. Sorghum breeding in the genomic era: opportunities and challenges. Theor Appl Genet. 2021;134:1899–924.
5. Mullet J, Morishige D, McCormick R, Truong S, Hilley J, McKinley B, Anderson R, Olson SN, Rooney W. Energy sorghum—a genetic model for the design of $C_4$ grass bioenergy crops. J Exp Bot. 2014;65(13):3479–89.

6. Mathur S, Umakanth AV, Tonapi VA, Sharma R, Sharma MK. Sweet sorghum as biofuel feedstock: recent advances and available resources. Biotechnol Biofuels. 2017;10:146.
7. Reddy PS, Reddy BVS. History of sorghum improvement. In: Aruna C, Visarada KBRS, Venkatesh Bhat B, Tonapi VA, editors. Breeding sorghum for diverse end use, vol. 16. Duxford: Woodhead Publishing; 2018. p. 255–70.
8. Diao X. Production and genetic improvement of minor cereals in China. Crop J. 2017;5:103–14.
9. Xin Z, Aiken R. Sorghum, a promising multiple-use crop for dry and hot climates. Planta. 2022;255:83.
10. National Bureau of Statistics of China. China statistical yearbook. 2021. http://www.stats.gov.cn/tjsj/ndsj/2021/indexch.htm. Accessed 12 Jan 2022.
11. Ma G, Oxley L, Gibson J, Li W. A survey of China's renewable energy economy. Renew Sust Energy Rev. 2010;14(1):438–45.
12. NDRC (National Development and Reform Commission), NEA (National Energy Administration). The 14th five-year plan for modern energy system. 2022. http://www.gov.cn/zhengce/zhengceku/2022-03/23/content_5680759.htm. Accessed 29 Jan 2022.
13. Mehmood MA, Ibrahim M, Rashid U, Nawaz M, Ali S, Hussain A, Gull M. Biomass production for bioenergy using marginal lands. Sustain Prod Consum. 2017;9:3–21.
14. Khanna M, Chen L, Basso B, Cai X, Field JL, Guan K, Jiang C, Lark TJ, Richard TL, Spawn-Lee SA, Yang P, Zipp KY. Redefining marginal land for bioenergy crop production. Glob Change Biol Bioenergy. 2021;13:1590–609.
15. Jiang D, Hao M, Fu J, Liu K, Yan X. Potential bioethanol production from sweet sorghum on marginal land in China. J Clean Prod. 2019;220:225–34.
16. Yan L, Zhang L, Wang S, Hu L. Potential yield of bioethanol from energy crops and their regional distribution in China. Trans Chin Soc Agric Eng. 2008;24(5):213–6.
17. Umakanth AV, Ashok Kumar AWV, Tonapi VA. Sweet sorghum for biofuel industry. In: Aruna C, Visarada KBRS, Venkatesh Bhat B, Tonapi VA, editors. Breeding sorghum for diverse end use, vol. 16. Duxford: Woodhead Publishing; 2018. p. 255–70.
18. Ding N, Yang Y, Cai H, Liu J, Ren L, Yang J, Xie G. Life cycle assessment of fuel ethanol produced from soluble sugar in sweet sorghum stalks in North China. J Clean Prod. 2017;161:335–44.
19. Fu J, Yan X, Jiang D. Assessing the sweet sorghum-based ethanol potential on saline–alkali land with DSSAT model and LCA approach. Biotechnol Biofuels. 2021;14:44.
20. Fu H, Chen Y, Yang X, Di J, Xu M, Zhang B. Water resource potential for large-scale sweet sorghum production as bioenergy feedstock in northern China. Sci Total Environ. 2019;653:758–64.
21. Jain S, Kumar S. A comprehensive review of bioethanol production from diverse feedstocks: current advancements and economic perspectives. Energy. 2024;296: 131130.
22. Hoogenboom G, Porter CH, Boote KJ, Shelia V, Wilkens PW, Singh U, White JW, Asseng S, Lizaso JI, Moreno LP, Pavan W, Ogoshi R, Hunt LA, Tsuji GY, Jones JW. The DSSAT crop modeling ecosystem. In: Boote KJ, editor. Advances in crop modeling for a sustainable agriculture. Cambridge: Burleigh Dodds Science Publishing; 2019. p. 173–216.
23. Hoogenboom G, Porter CH, Shelia V, Boote KJ, Singh U, Pavan W, Oliveira FAA, Moreno-Cadena LP, Ferreira TB, White JW, Lizaso JI, Pequeno DNL, Kimball BA, Alderman PD, Thorp KR, Cuadra SV, Vianna MS, Villalobos FJ, Batchelor WD, Asseng S, Jones MR, Hopf A, Dias HB, Hunt LA, Jones JW. Decision support system for agrotechnology transfer (DSSAT) version 4.8.2. 2023. www.DSSAT.net.
24. Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ, Ritchie JT. The DSSAT cropping system model. Eur J Agron. 2003;18:235–65.
25. Fu J, Jiang D, Huang Y, Zhuang D, Ji W. Evaluating the marginal land resources suitable for developing bioenergy in Asia. Adv Meteorol. 2014;9: 238945.
26. Jiang Z, Lian Y, Qin X. Rocky desertification in Southwest China: impacts, causes, and restoration. Earth Sci Rev. 2014;132:1–12.
27. Fu J, Du J, Lin G, Jiang D. Analysis of yield potential and regional distribution for bioethanol in China. Energies. 2021;14(15):4554.
28. Wang H, Chen G, Zhang H, Liu B, Yang Y, Qin L, Chen E, Guan Y. Identification of QTLs for salt tolerance at germination and seedling stage of *Sorghum bicolor* L. Moench. Euphytica. 2014;196(1):117–27.
29. Lu QS. Sweet sorghum. Beijing: China Agriculture Scientech Press; 2008.
30. Mosier AR, Halvorson AD, Reule CA, Liu XJ. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in Northeastern Colorado. J Environ Qual. 2006;35:1584–98.
31. Jones JW, He J, Boote KJ, Wilkens P, Porter CH, Hu Z. Estimating DSSAT cropping system cultivar-specific parameters using Bayesian techniques. In: Ahuja LR, Ma L, editors. Methods of introducing system models into agricultural research, vol. 2. Madison: ASA, CSSA, SSSA; 2011. p. 365–93.
32. Sannagoudar MS, Patil RH, Rajanna GA. Calibration and evaluation of DSSAT-CERES model for kharif sorghum genotypes. J Exp Agric Int. 2019;30(3):2457–0591.
33. Yan X, Jiang D, Fu J, Hao M. Assessment of sweet sorghum-based ethanol potential in China within the water–energy–food nexus framework. Sustainability. 2018;10:10462.
34. Tian Y, Li S, Zhao L, Meng H, Huo L. Life cycle assessment on fuel ethanol producing from sweet sorghum stalks. Trans Chin Soc Agric Mach. 2011;42(06):132–7 (**in Chinese**).
35. Zhuang D, Jiang D, Liu L, Huang Y. Assessment of bioenergy potential on marginal land in China. Renew Sust Energy Rev. 2011;15(2):1050–6.
36. NEA (National Energy Administration). The 13th five-year plan for biomass energy development. 2016. http://www.gov.cn/xinwen/2016-12/06/content_5143612.htm. Accessed 6 Dec 2016.
37. Almodares A, Hadi MR. Production of bioethanol from sweet sorghum: a review. Afr J Agric Res. 2009;4(9):772–80.
38. Li Y, Song T, Lai Y, Huang Y, Fang L, Chang J. Status, mechanism, suitable distribution areas and protection countermeasure of invasive species in the karst areas of Southwest China. Front Environ Sci. 2022;10: 957216.
39. Liu M, Han G. Assessing soil degradation under land-use change: insight from soil erosion and soil aggregate stability in a small karst catchment in southwest China. PeerJ. 2020;8: e8908.
40. National Bureau of Statistics of China. Statistical bulletin of the People's Republic of China on national economic and social development for 2023. 2024. https://app.www.gov.cn/govdata/gov/202403/01/512478/article.html. Accessed 29 Feb 2024.
41. Cao X, Sun B, Chen H, Zhou J, Song X, Liu X, Deng X, Li X, Zhao Y, Zhang J, Li J. Approaches and research progresses of marginal land productivity expansion and ecological benefit improvement in China. Proc Natl Acad Sci Chin. 2021;36(03):336–48.
42. Ren L, Liu Z, Wei T, Xie G. Evaluation of energy input and output of sweet sorghum grown as a bioenergy crop on coastal saline-alkali land. Energy. 2012;47(1):166–73.
43. Hao M, Fu J, Jiang D, Yan X, Chen S, Ding F. Sustainable development of sweet sorghum-based fuel ethanol from the perspective of water resources in China. Sustainability. 2018;10(10):3428.
44. Li H, Wang L. Evaluation of $CO_2$ emission reduction potential of non-grain fuel ethanol development in China. J Nat Resour. 2012;27(02):225–34.
45. Anami S, Zhang L, Xia Y, Zhang Y, Liu Z, Jin H. Sweet sorghum ideotypes: genetic improvement of the biofuel syndrome. Food Energy Secur. 2015;4(3):159–77.
46. Zhang H, Yu F, Xie P, Sun S, Qiao X, Tang S, Chen C, Yang S, Mei C, Yang D, Wu Y, Xia R, Li X, Lu J, Liu Y, Xie X, Ma D, Xu X, Liang Z, Feng Z, Huang X, Yu H, Liu G, Wang Y, Li J, Zhang Q, Chen C, Ouyang Y, Xie Q. A Gγ protein regulates alkaline sensitivity in crops. Science. 2023;379: eade8416.
47. Tang C, Li S, Li M, Xie G. Bioethanol potential of energy sorghum grown on marginal and arable lands. Front Plant Sci. 2018;9:440.
48. Xie Q, Xu Z. Sustainable agriculture: from sweet sorghum planting and ensiling to ruminant feeding. Mol Plant. 2019;12(5):603–6.

## Publisher's Note