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Technical Feasibility and Comprehensive Sustainability Assessment of Sweet Sorghum for Bioethanol Production in China

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Abstract: Under dual pressures of energy and environmental security, sweet sorghum is becoming one of the most promising feedstocks for biofuel production. In the present study, the technical feasibility of sweet sorghum production was assessed in eight agricultural regions in China using the Sweet Sorghum Production Technique Maturity Model. Three top typical agricultural zones were then selected for further sustainability assessment of sweet sorghum production: Northeast China (NEC), Huang-Huai-Hai Basin (HHHB) and Ganxin Region (GX). Assessment results demonstrated that NEC exhibited the best sustainable production of sweet sorghum, with a degree of technical maturity value of 0.8066, followed by HHHB and GX, with corresponding values of 0.7531 and 0.6594, respectively. Prospective economic profitability analysis indicated that bioethanol production from sweet sorghum was not feasible using current technologies in China. More efforts are needed to dramatically improve feedstock mechanization logistics while developing new bioethanol productive technology to reduce the total cost. This study provides insight and information to guide further technological development toward profitable industrialization and large-scale sweet sorghum bioethanol production.

Keywords: sweet sorghum; technical feasibility; sustainability assessment; bioethanol production potential; economic profitability

1. Introduction

The increasing world population and the rapid development of a global economy created a huge strain on energy resources and the environment [1]. Recently, China has become the country that consumes the most energy worldwide, surpassing even the USA [2]. Meanwhile, high energy consumption has placed great pressure on the environment in diverse ways, including increases in greenhouse gas emissions (GHGs). Due to these concerns, the search for alternative sources of energy has become the highest priority for China's government [3]. Biofuels are regarded as the best alternative fuel source, due to their renewability and less environmental pollution [4,5] and bioethanol is the main biofuel currently in use [6]. However, China faces high demand for food in addition to high energy demands. Therefore, any bioenergy program must ultimately maintain a balance between food and fuel. Maintaining this balance has been a difficult task, as ethanol production using corn grain has previously been reported to be ecologically unsustainable [7] and conflicting with food security priorities [8,9]. Meanwhile, sweet sorghum [*Sorghum bicolor* (L.) Moench] has become a promising non-food energy crop [10], due to its high biomass, saline-alkaline resistance [11], drought-tolerance [12,13] and the large amounts of fermentable carbohydrates in its juice-rich stalks [14,15]. In addition, sorghum cultivation has been reported to be sustainable with the use of crop rotation [10,16].

Much progress has been made through extensive research conducted on sweet sorghum worldwide. Therefore, abundant knowledge has been obtained with regard to breeding, genetics and variety selection [16,17], crop physiology [18,19] and production techniques [19–21]. Advances in production techniques have been made in areas including irrigation [11,22], fertilizer use [22,23], nutrient uptake [24], plant density [20,25,26], harvest date [14,15,25] and lodging control. In the areas of Tianjin, Anhui, Hainan, Heilongjiang, Xinjiang and Inner Mongolia, a previous study [26] demonstrated that the effect of environmental impact factor (E) on sweet sorghum growth was greater than either G (genotype) or the G × E (interaction effect) based on the Radial Basis Function (RBF) network model with stepwise regression. It has also been reported [27] that sweet sorghum can grow in extreme environmental conditions, such as in regions with an annual effective accumulated temperature greater than 2500 degree days (above 10 °C), soil pH between 5.0–8.5 and soil gravel content <85%. Other research [28] has clarified that soil pH, total nitrogen and available potassium exert great influence on relative yield and quality of sweet sorghum, subsequently leading to additional studies focusing on yield and production potential of sweet sorghum for bioethanol production [3,11,14,29,30]. One study reported that bioethanol from sweet sorghum could reach 1250–5625 L/ha, equal to that obtained from 9000–11,250 kg of grain crop [29]. Meanwhile, the economic benefit of growing sweet sorghum was estimated to approach 1214 USD/ha, a much higher benefit than for soybean or corn, crops that are already profitable for farmers. Another study [31] demonstrated that ethanol yield produced from sweet sorghum (6106 L/ha) was much higher than that of sugarcane (4680 L/ha). Another study [14] reported general grain and stalk yields of 2.3–3.0 t/ha and 67.5–82.5 t/ha, respectively, with 12–18% sugar content in juice; fuel ethanol production could reach as high as 5250 L/ha. However, systematic reports on the yield and feasibility of various sweet sorghum cultivation practices for bioethanol production spanning all agricultural zones of China have rarely been published.

Recently, more efforts have been expended to study overall energy output [32,33], ecological sustainability [34] and economic benefit [31,35–38] of sweet sorghum as a bioethanol feedstock. One study reported that sweet sorghum had a lower energy input requirement and a higher energy productivity than cotton and maize on the coastal saline-alkaline lands in Shandong Province and Inner Mongolia [33]. Meanwhile, another study demonstrated that development of sweet sorghum bioethanol relieved energy constraints, was conducive to agricultural production and industrial progress, while being favorable to the environment [31]. Moreover, the net economic output of sweet sorghum cultivation has also been reported to be significantly higher than for other staple crops in Xinjiang and Shandong Province [31,35]. Other research [32] has reported good sustainability, higher resource utilization, lower GHGs and lower need for pesticide application in sweet sorghum production in China, oil palm in Southeast Asia and sugarcane in Brazil; this compared favorably with poor sustainability for corn grown in the U.S. and wheat grown in northwestern Europe. Economically, the net revenue of the commercial sweet sorghum bioethanol industry reached 219×10^4 USD/ha, with a return on investment of 15.11% in a seven-year investment recovery period [36]. Meanwhile, another group [31] reported that the cost of bioethanol production using sweet sorghum is much lower, by around 46.5–57.5%, than costs using sugar beet feedstock; this agrees with another study [38] reporting consistently lower production costs of sweet sorghum as ethanol feedstock than costs for competing crops such as corn, cotton and soybean, as demonstrated by economic feasibility analysis in the southeastern U.S. After economic analysis [35], sweet sorghum as an energy crop for ethanol production showed a better return to scale on investment than cotton and sunflower in North China. Indeed, the large-scale cultivation and processing of sweet sorghum was reported to increase the farms' economic incomes, reduce the cost of production and conversion and promote the development of husbandry, sugar manufacturing, bioenergy and papermaking [37]. However, a comprehensive sustainability assessment of sweet sorghum including cultivation, energy and economic input-output ratio, environmental effects, etc., has not yet been done for the major agricultural regions across China.

Because sweet sorghum holds great promise as a highly advantageous renewable bioenergy crop, more research is needed in order to support large-scale utilization of this crop for bioenergy production. In the handful of published studies, previous energy efficiency and economic benefit analyses of sweet sorghum conversion to bioethanol have mainly focused on a specific region or a single aspect of the process. Consequently, both a comprehensive sustainability assessment of cultivation practices and a thorough economic feasibility evaluation of bioethanol production for sweet sorghum in the various farming zones across China are needed. Therefore, the objectives of this study are to (1) identify the technical feasibility of sweet sorghum production in major farming zones across China; (2) analyze the sustainability of sweet sorghum production based on a literature review and investigate promising topics comprehensively; (3) reveal the prospective economic profitability of sweet sorghum bioethanol production as biomass feedstock using the current bioethanol conversion technology in China.

2. Materials and Methods

2.1. Agricultural Zones

According to the book of "Agricultural Resources and Regional Planning in China" [39], the nation was divided into geographical farming zones comprised of county administrative districts by considering social, economic and basic agricultural production practices, as well as developmental direction and main production problems and solutions (Figure 1). These zones are designated as Northeast China (NEC), Huang-Huai-Hai Basin (HHHB), Ganxin Region (GX), Inner-Mongolia and zone along the Great Wall (IZG), Loess Plateau (LP), Southwest China (SWC), Middle-lower area of Yangtze Basin (MLYB), South China (SC) and Qinghai plus Tibet plateau (QT). Due to the cold climate in QT, sweet sorghum is rarely planted there [40]. QT was excluded, leaving eight zones to analyze.
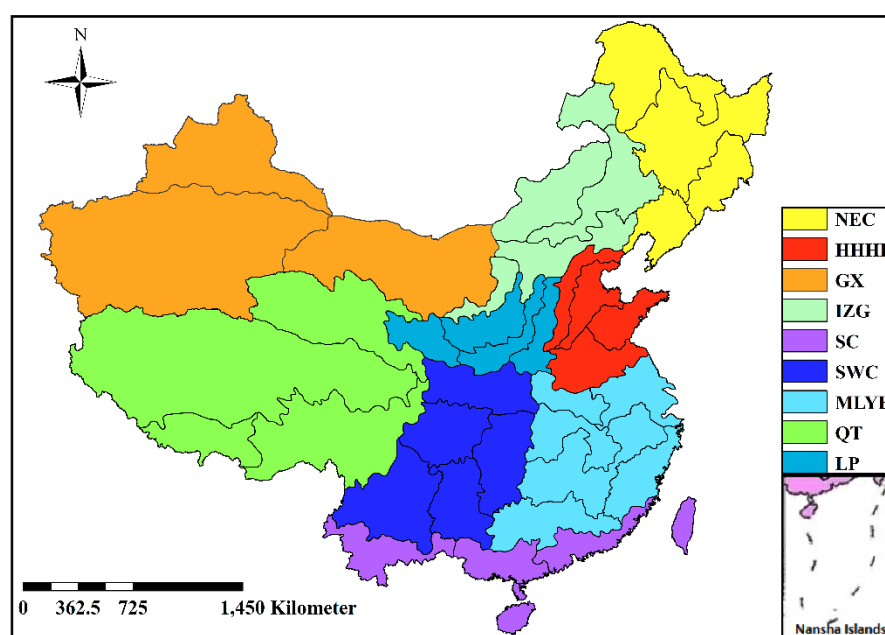

Figure 1. Comprehensive agricultural zoning map in China.

2.2. Evaluation of Technical Feasibility of Sweet Sorghum Production

In this study, a research literature review of sweet sorghum grown in the major farming regions was performed and the bulk of the work was divided into four categories: breeding techniques (variety selection, introduction and breeding, genetics, etc.), cultivation management (cultivation technology such as plant density, sowing date, fertilization, etc.), storage techniques (storage experiments in each region) and stress physiology (drought, salinity and alkalinity, heavy metals, etc.). All references

were obtained from published Chinese and English research literature using "sweet sorghum" as keyword and limiting the search results to the most recent 15 years for searching of databases including "Web of Science," "China Knowledge Resource Integrated (CNKI)" and the "WanFang Database." The aforementioned indicators were used to compare and analyze the Degree of Technical Maturity (DTM) of sweet sorghum production in various regions. Each phase of sweet sorghum production is also affected by local economic development and climatic conditions.

A rapid analysis method designated as the "Sweet Sorghum Production Technique Maturity Model (SPTM)" in this study was used to evaluate the degree of technical maturity (DTM) of sweet sorghum production practices in various regions, as assessed using the aforementioned four indicators (breeding, cultivation, storage and stress-resistance). The calculation codes of SPTM are detailed in Supplementary Materials File 1. The proposed technique is based on the theory of Grey Relational Grade Analysis (GRGA), which is one of the essential components of grey systems theory formulated by Deng [41]. The weights of the studied indicators were defined according to the evaluation criteria and the DTM assessment determined in this study. Breeding technique, cultivation management and storage technique are the key indicators of sweet sorghum production. The weights of these three indicators were each assigned a value of 0.3 in this study. The weight of the indicator of stress physiology was assigned to be 0.1, due to sweet sorghum's strong resistance to environmental stresses. Assuming that the DTM has a positive correlation with the numbers of discovered local research publications, the maximum value of each indicator across eight regions was regarded as the indicator's theoretical optimum value. This method uses matrix calculation to quantify the data in different levels and transforms multiple responses into a single grey relational grade, so that the DTM could be comprehensively and fairly evaluated with a single dimensionless value. The DTM was assigned to one of four grades reflecting the technical level of sweet sorghum production, including very immature, immature, generally mature and mature, where the corresponding DTM ranged between [0, 0.25], [0.25, 0.50], [0.50, 0.75] and [0.75, 1.00], respectively.

2.3. Comprehensive Sustainability Assessment of Sweet Sorghum Production

Based on the results of the technical feasibility evaluation, three typical agricultural production regions, including NEC, HHHB and GX, were selected to represent the various soil and climate types and were subjected to comprehensive sustainability assessment of sweet sorghum production. In each of these three zones, typical study sites in the zone's main planting area of sweet sorghum were selected according to the natural environmental conditions and planting characteristics [37]. The main conditions including position, climate and soil characteristics of the selected study sites are detailed in Table 1.

The sustainability assessment boundary began with soil preparation and included film mulching, basal fertilizer dressing, sowing, thinning out of seedlings, weeding, tiller removal, topdressing, pesticide application, irrigation, spikelet removal, harvesting, bundling, transportation, threshing to storage and marketing (Figure 2).
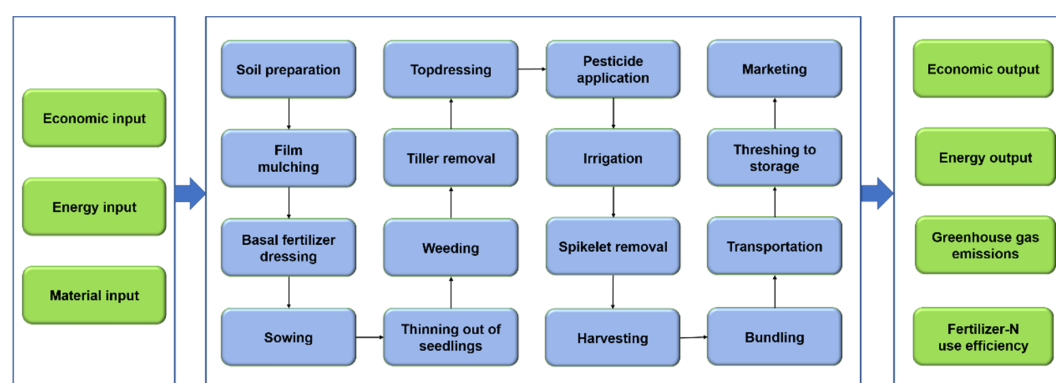

Figure 2. Sustainability assessment boundary in typical agricultural production regions.

Table 1. Main characteristics of the selected typical study sites in this study.

Item	Unit	Northeast China (NEC) [#]		Huang-Huai-Hai Basin (HHHB) [#]		Ganxin Region (GX) [#]		
		Huachuan *	Morin Dawa *	Wudi *	Wendeng *	Turpan *	Wuyuan *	Gulang *
Position:								
East-longitude		130°16′–131°34′	123°33′–125°16′	117°31′–118°04′	121°57′–122°17′	87°14′–91°54′	107°35′–108°37′	102°38′–103°54′
North latitude		46°31′–47°14′	48°05′–49°55′	37°41′–38°16′	36°19′–37°55′	41°12′–43°35′	40°46′–41°16′	37°09′–37°54′
Altitude	m	60–70	173–638.3	50	257	−154–4000	1019–1035	1550–3469
Climate:								
Precipitation	mm	476.4	400–500	598.6	768.4	3.9–25.5	177	250
Annual average temperature	°C	2.5	3.2	12.1	11.4	13.9	6.1	5.2
Annual highest temperature	°C	36.8	39.5	26	24.6	32.7	22.7	37.2
Annual lowest temperature	°C	−39.7	−45	−4	−1.4	−9.5	−13.2	−26.4
accumulated temperature ≥10 °C	°C	2500–2700	1815–2413	4339	4000	5455	2896	2686
Frost-free season	day	133	100–134	206	221	250–300	117–136	150
Annual sunshine hours	h	2500–2600	2500–2800	2724.5	2512	3056	3231	2852
Annual average evaporation	mm	1275	1050–1450	1238	1500–1700	2879–3822	2039	2807
Soil:								
pH value		6.62	6.8	7.0–7.5	6.8	8.6–9.1	8.4	8.0
Organic matter	%	4.46	4.15–10.0	1.31	1.2	4.04	1.17	1.54
Total nitrogen	%	0.23	0.28–0.67	0.47	0.71	0.22	0.54	0.096
Available N	mg/kg	163.7	N/A	58.53	N/A	63.56	52.37	75.5
Available P	mg/kg	27.9	18.26	15.32	26	55.03	14.17	6.05
Available K	mg/kg	158.3	150–200	158.45	51	165.67	157.9	N/A
Reference		[9,42]	[43–45]	[46–48]	[49–51]	[52,53]	[54–56]	[57–59]

[#] denotes the selected three zones after the technical feasibility evaluation. * denotes the selected typical study sites in each zone.

In order to make a comprehensive sustainability assessment, the National Energy R&D Center for Non-food Biomass (NECB) obtained a total of 481 questionnaires based on face-to-face interviews with farmers in NEC (Morin Dawa Banner), HHHB (Wudi County and Wendeng County) and GX (Wuyuan County) during a four-year sustainability analysis of sweet sorghum production supported by National Energy Administration of China [33,35].

Multiple evaluation factors of sustainability assessment included energy efficiency, environmental effects, economic benefit, etc., as described below.

(1)　Energy output

In this study, the energy efficiency evaluation was based on two indices. One was the energy input-output ratio of sweet sorghum production, which was defined as the energy contained in both the stalk, as the main product and the grain, as the by-product, divided by the energy consumed in the cultivation and transportation of the sweet sorghum. Considering the scarcity of land resources in China, the available land area is of utmost importance for calculating sweet sorghum energy production. The other important indicator is net energy output per unit of land area, which was defined as the energy contained in the stalk and the grain minus the energy consumed in the cultivation and transportation of the sweet sorghum.

(2)　Greenhouse gas emissions

Reducing the greenhouse gas emissions (GHGs) was the original intent behind development of biofuels [48]. Notably, the sweet sorghum cultivation phase is the main source of greenhouse gas emissions in bioethanol life cycle, including the use of diesel fuel and electricity consumption to conduct irrigation, as well as the production and application of nitrogen fertilizer [22]. The GHGs, as the second indicator, consist of the emissions generated during the growth and transportation of sorghum straw per kilogram. The economic value approach was applied to allocate the percentages of the emissions to the stalks as main products and to grains as by-products in the sweet sorghum cultivation phase.

(3)　Economic benefit

The economic profitability of the farmers directly influences whether they plant bioenergy crops instead of conventional food crops. Therefore, assessment of profitability is crucial to the development of bioenergy crops for production of liquid biofuels [1]. Farmers' incomes correlate directly to planting costs, biomass yield and market price of sweet sorghum [35]. In this study, the economic input-output ratio, as another indicator, was defined as the economic output of both the stalks as main products and grain as by-products divided by the cost input of sweet sorghum's production and transportation. The net economic output is the difference between the economic output and input.

(4)　Nitrogen fertilizer

Fertilizer-leaching pollution, especially of nitrogen and phosphorus fertilizers applied during agricultural production, is both detrimental to ecosystems and to drinking water quality [4]. This study focuses on the N fertilizer, which had the strongest influence on sustainable development. N fertilizer generation consumes much energy and causes a vast quantity of GHGs that increase in direct proportion with N application. The N fertilizer use efficiency [60], as an indicator, was defined as the net energy produced per kg of N fertilizer application. Cultivation practices of sweet sorghum are relatively simple in China, with little application of either pesticides or irrigation [35], thus, these factors were ignored in this study.

Assuming that the weights of the effects of the above indicators on the sustainability of sweet sorghum production are equal, we took the maximum value of each indicator (except GHGs) as 100 for the degree of sustainability, with the others calculated in proportion. As for the greenhouse

gas emissions, the minimum is the basal value, defined as 100 and the value of other emissions is calculated using the formula:

$$y = (\text{other emission} - \text{minimum emission})/\text{minimum emission} \times 100 - 100 \qquad (1)$$

2.4. Economic Profitability Assessment of Sweet Sorghum Bioethanol Production

2.4.1. Theoretical Bioethanol Production Potential for Selected Sites

In view of the lack of commercial scale sweet sorghum cultivation in China, a demonstration process was developed and evaluated based on Advanced Solid-State Fermentation (ASSF) technology with minor modifications [61,62]. In this scheme, bioethanol was produced by conversion of starch extracted from grain and from sugar in stem juice (Figure 3). The conversion factors of fuel ethanol from grain and juice were 430.38 L/t and 79.11 L/t, respectively. Using this system, the theoretical production potential of ASSF could be calculated as follows.

$$\text{Ethanol yield from grain (L/ha)} = 430.38 \text{ (conversion factor of fuel ethanol from grain, L/t)} \times \text{grain yield (t/ha)} \qquad (2)$$

$$\text{Ethanol yield from juice (L/ha)} = 79.11 \text{ (conversion factor of fuel ethanol from juice, L/t)} \times \text{stem yield (t/ha)} \qquad (3)$$

$$\text{Total ethanol yield from sweet sorghum (L/ha)} = \text{Ethanol yield from grain (L/ha)} + \text{Ethanol yield from juice (L/ha)} \qquad (4)$$
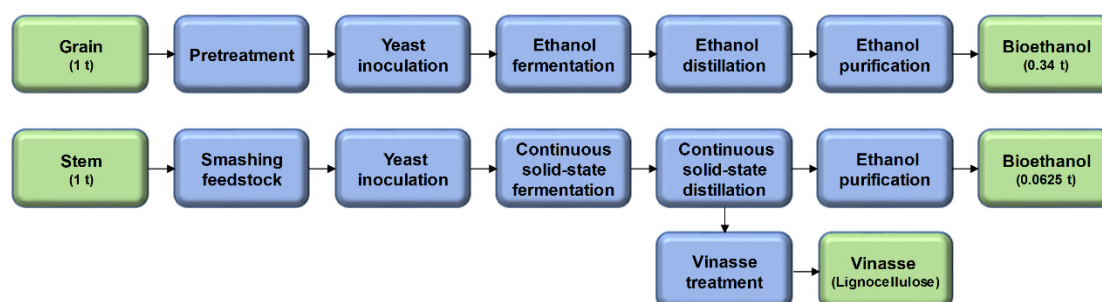

Figure 3. Schematic representation of Advanced Solid-State Fermentation (ASSF).

2.4.2. Prospective Economic Profitability of ASSF for Selected Sites

In 2002, the Chinese central government issued the "Announcement on Issue of Detailed Rules of Implementation for the Extension of the Pilot Program of Ethanol Alcohol Gasoline for Vehicles" ([2004] 230) to officially set the price of fuel ethanol, which is calculated as 0.911 times the market price of 93 octane gasoline. For a reliable calculation of prospective economic profitability, the price of fuel ethanol was set to 0.97 USD/kg based on the average value from 2011 to 2015 [30]. According to our previous study, the price of sweet sorghum logistics including storage and transportation is 52.64 USD/t for the current biomass feedstock supply in North China [1]. The cost of grain ethanol production (632.23 USD/t) included the purchase cost of grain feedstock from farmers and the cost of the ethanol conversion process [62]. Similarly, the cost of stem juice ethanol production (615.4 USD/t) included the purchase cost of stem feedstock from farmers and the cost of the ethanol conversion process [61]. The prospective economic profitability of ASSF would then be calculated as follows:

$$\text{Economic inputs of sweet sorghum logistics (USD/ha)} = 52.64 \text{ (the price of sweet sorghum logistics, USD/t)} \times \text{biomass yield (the sum of grain and stem yield, t/ha)} \qquad (5)$$

$$
\begin{aligned}
\text{Economic inputs of fuel ethanol production (USD/ha)} = {}& 632.23 \text{ (the cost of fuel} \\
& \text{ethanol production from grain, USD/t)} \times \text{ethanol yield from grain (L/ha)} \\
& \times 0.79 \text{ (specific gravity of ethanol, kg/L)}/1000 + 615.4 \text{ (the cost of fuel ethanol} \\
& \text{production from stem, USD/t)} \times \text{ethanol yield from stem (L/ha)} \\
& \times 0.79 \text{ (specific gravity of ethanol, kg/L)}/1000
\end{aligned}
\tag{6}
$$

$$
\begin{aligned}
\text{Economic outputs of fuel ethanol production (USD/ha)} = {}& 0.97 \text{ (USD/kg)} \times \text{total ethanol} \\
& \text{yield from sweet sorghum (L/ha)} \times 0.79 \text{ (specific gravity of ethanol, kg/L)}/1000
\end{aligned}
\tag{7}
$$

$$
\begin{aligned}
\text{Theoretical net economic output (USD/ha)} = {}& \text{outputs of fuel ethanol} \\
& \text{production (USD/ha)} - \text{inputs of sweet sorghum logistics (USD/ha)} - \text{inputs of fuel} \\
& \text{ethanol production (USD/ha)}
\end{aligned}
\tag{8}
$$

2.5. Statistical Analysis

The sweet Sorghum Production Technique Analysis Model (SPTM) was developed using MATLAB 2014b (The MathWorks Inc., Natick, MA, USA); the procedure code can be found in Supplementary Materials File 1. Means, standard deviations and ANOVA analyses were calculated using IBM SPSS Statistics V.24 (IBM SPSS Inc., Chicago, IL, USA). China Agricultural Resources and Regional Planning Map was made using ArcGIS 10.3 (ESRI Inc., Redlands, CA, USA) and all figures were handled by OriginPro 9.1 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. The Technical Feasibility of Sweet Sorghum Production in China

As presented in Table 2, normalized publication counts and the weighted DTM index of sweet sorghum were determined using the dedicated SPTM. The DTM of sweet sorghum was highest in the NEC among others (0.8066), followed by the GX (0.7531) and YHH (0.6594) (Table 2), which were all greater than 0.5. Notably, the production DTM level was mature for NEC and GX and generally mature in HHHB. Conversely, DTM values were between 0.3 and 0.4 in the other five areas, which demonstrated that sweet sorghum technology was immature. The ranking of DTM values from high to low in these five regions was MLYB (0.3967) > LP (0.3670) > SC (0.3634) > IZG (0.3564) > SWC (0.3564).

Table 2. Technical level of sweet sorghum production in the four categories and the weighted Degree of Technical Maturity (DTM) in different agricultural zones of China.

Agriculture Region *	Breeding Technique	Cultivation Technique	Storage Technique	Stress-Resistance Physiology	DTM	Ranking
NEC	1.0000	1.0000	0.5385	0.4510	0.8066	1
GX	0.4851	0.8750	1.0000	0.4510	0.7531	2
HHHB	0.4757	1.0000	0.3889	1.0000	0.6594	3
MLYB	0.3379	0.3784	0.4667	0.4182	0.3967	4
LP	0.3630	0.3415	0.3684	0.4510	0.3670	5
SC	0.4336	0.3333	0.3333	0.3333	0.3634	6
IZG	0.3333	0.3684	0.3684	0.3538	0.3564	7
SWC	0.3333	0.3415	0.3333	0.3333	0.3358	8

* NEC: Northeast China, IZG: Inner-Mongolia and Zone along the great wall, HHHB: Huang-Huai-Hai Basin, GX: Ganxin Region, LP: Loess Plateau, SWC: Southwest China, MLYB: Middle-lower reaches of Yangtze Basin, SC: South China.

3.2. Comprehensive Sustainability Assessment of Sweet Sorghum Production

Due to their highest DTM values, three agricultural production zones, NEC, HHHB and GX, were chosen to conduct a comprehensive sustainability assessment of sweet sorghum production.

Summary statistics of economic, energy-saving and environmental benefits of sweet sorghum production in NEC, HHHB and GX are detailed in Table 3.

Table 3. Indicators of the sustainability of sweet sorghum production of typical study sites in Northeast China, Huang-Huai-Hai Basin and Ganxin Region.

Indicator	Unit	Northeast China		Huang-Huai-Hai Basin		Ganxin Region	
		Sample Site Numbers	Average Value	Sample Site Numbers	Average Value	Sample Site Numbers	Average Value
Economic input	USD/ha	2	904.8	3	1282.2	2	2129.0
Economic output	USD/ha	2	1814.0	3	2263.5	2	3806.5
Net economic output	USD/ha	2	909.3	3	981.4	2	1677.5
Economic input-output ratio		2	2.28	3	1.79	2	1.86
Energy input	GJ hm^{-2}	1	27.1	2	27.9	1	43.2
Energy output	GJ hm^{-2}	1	387.3	2	300.6	1	204.5
Net energy output	GJ hm^{-2}	1	360.2	2	272.7	1	161.3
Energy input-output ratio		1	14.28	2	10.8	1	4.7
Greenhouse gas emissions	g CO_2-eq/kg stalk	1	29.1	1	53.7	1	35.6
Amount of Fertilizer-N	kg N ha^{-1}	1	45.8	1	211.4	1	126.9
N fertilizer-use efficiency	GJ kg^{-1} N	1	7.86	1	1.29	1	1.27
Reference		[36,63], survey data		[33,63,64]		[33,57,63]	

Sample sits of Northeast China comes from the typical study sites of Huachuan, Morin Dawa and East Heilongjiang; sample sits of Huang-Huai-Hai Region comes from Wudi, Wendeng, Cangzhou and North Shandong; sample sites of Ganxin Region comes from Wuyuan, Gulang and Middle Xinjiang. Each of the typical study sites was detailed in Table S1 of Supplementary Materials File 2.

Results showed that the average economic input value of sweet sorghum production was lowest for NEC with the average value of 904.8 USD/ha, followed by HHHB with the average value of 1282.2 USD/ha and the highest in GX with the average value of 2129.0 USD/ha. Economic output value of sweet sorghum production was lowest for GX with the average value of 3806.5 USD/ha, followed by HHHB with the average value of 2263.5 USD/ha and highest for NEC with the average value of 1814.0 USD/ha (Table 3). No significant differences were observed among the two available study sites in NEC and among the three available study sites in HHHB (Table S1). The average net economic output value of sweet sorghum production was lowest for NEC with the average value of 909.3 USD/ha, followed by HHHB with the average value of 981.4 USD/ha and highest for GX with the average value of 1677.5 USD/ha. However, there were large differences among the two available sites in GX where the net economic output of Wuyuan County was negative, around −642.3 USD/ha, while that of Gulang County was positive, approximately +3997.2 USD/ha (Table 3 and Table S1). Finally, the average economic input-output ratios in NEC, HHHB and GX were 2.28, 1.79 and 1.86, respectively.

The average energy input of sweet sorghum production was highest in Wuyuan County in GX (43.2 GJ/ha) and lower for NEC and HHHB (27.1 GJ/ha and 27.9 GJ/ha, respectively). Energy output was highest in NEC, with 387.3 GJ/ha in Morin Dawa Daur Autonomous Banner, followed by HHHB, with an average of 300.6 GJ/ha and the lowest in Ganxi with an average of 204.5 GJ/ha in Wuyuan County (Table 3 and Table S1). The ranking of net energy output was similar to that of the energy input-output ratio, with the order of NEC > HHHB > GX.

On a per kg stalk production basis, GHGs levels were determined after conversion to CO_2 equivalent (CO_2-eq) and were highest in HHHB with 53.7 g CO_2-eq/kg stalk in Wudi County, followed by GX, with 35.6 g CO_2-eq/kg stalk in Wuyuan County and lowest in NEC, with 29.1 g CO_2-eq/kg stalk in Huachuan County (Table 3 and Table S1). Finally, N-fertilizer application exhibited a positive correlation with the GHGs in each research region.

In order to create a visualized comprehensive evaluation of the six indicators of sustainability mentioned above, a spider diagram was adopted (Figure 4). The blue area in each picture represents the sustainability of sweet sorghum production in each research region; the bigger the size of the blue area, the higher sweet sorghum sustainability. It is obvious that the best sustainability of sweet sorghum

production was observed in NEC (Figure 4a), while relatively poor sustainability was observed in HHHB (Figure 4b) and GX (Figure 4c).
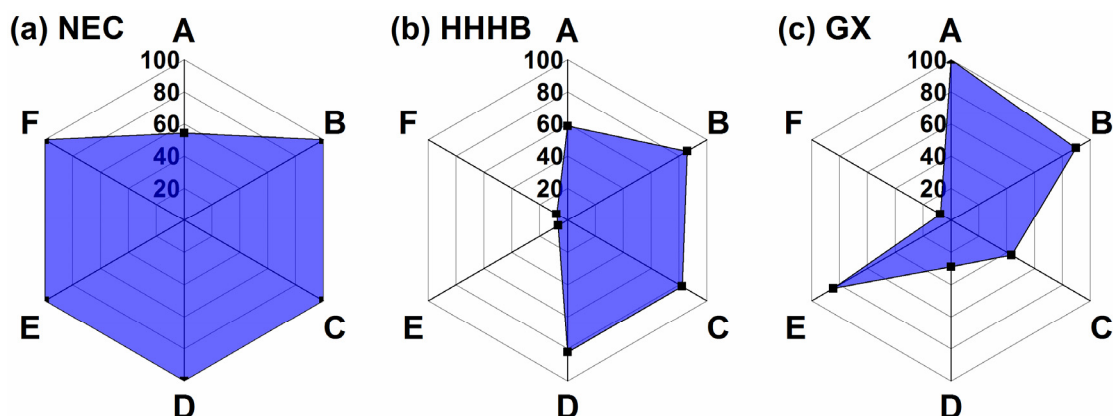

Figure 4. Comparison of the sustainability of sweet sorghum production in (**a**) Northeast China (NEC), (**b**) Huang-Huai-Hai Basin (HHHB) and (**c**) Ganxin Region (GX). A: Net economic output; B: Economic input-output ratio; C: Net energy output; D: Energy input-output ratio; E: Greenhouse gas emissions reduction; F: Nitrogen fertilizer use efficiency.

3.3. Analysis of Theoretical Bioethanol Productive Potential

Summary statistics of the grain and stem yields of sweet sorghum in NEC, HHHB and GX are shown in Table 4 [33,35]. Due to late-maturation and absence of a heading stage, no sweet sorghum grain was harvested in NEC. The average grain yield values of sweet sorghum in GX and HHHB were 1.9 t/ha and 2.1 t/ha, respectively. The average sweet sorghum stem biomass yield was highest in NEC with the average value of 75.0 t/ha, followed by HHHB with the average value of 68.9 t/ha, with the lowest value observed for GX (55.9 t/ha). Overall, NEC obtained the highest biomass yield (75.0 t/ha), followed by HHHB (71.0 t/ha) and GX (57.8 t/ha).

Table 4. Annual average grain and stem yield of sweet sorghum in Northeast China, Huang-Huai-Hai Basin and Ganxin Region.

Index	Northeast China	Huang-Huai-Hai Basin	Ganxin Region
Grain t/ha	0	2.1 ± 0.2	1.9 ± 0.9
Stem t/ha	75.0 ± 15.0	68.9 ± 3.8	55.9 ± 13.9
Biomass t/ha	75.0 ± 15.0	71.0 ± 4.0	57.8 ± 14.8

± represents standard deviation across studies.

To evaluate the theoretical bioethanol production potential of the three selected regions, a demonstration scenario was developed based on Advanced Solid-State Fermentation (ASSF) technology with minor modifications (Figure 3). The results demonstrated that the rank order of the theoretical ethanol yield of stem based on ASSF processing was similar to the rank order of biomass yield: NEC (5933.5 L/ha) > HHHB (5452.5 L/ha) > GX (4422.5 L/ha). Due to higher grain bioethanol yield, the total average bioethanol yield was highest in HHHB with the average value of 6322.4 L/ha, followed by NEC with the average value of 5933.5 L/ha, with lowest total bioethanol yield for GX (5228.7 L/ha) (Figure 5).
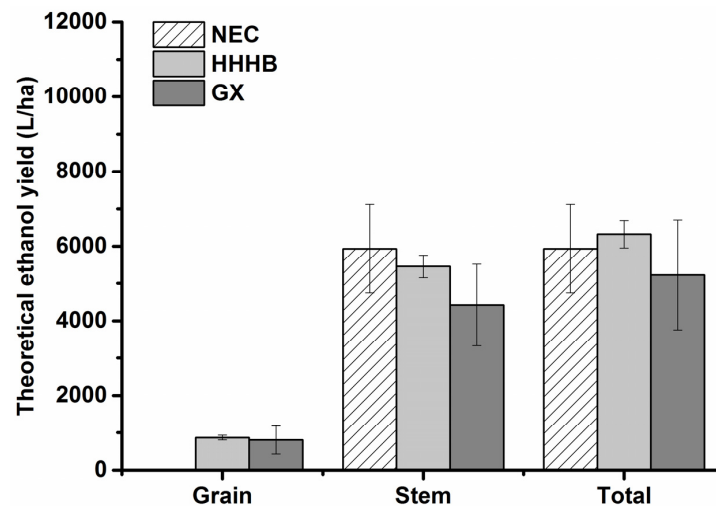
Figure 5. Theoretical bioethanol production potential of sweet sorghum from grain and stem in Northeast China (NEC), Huang-Huai-Hai Basin (HHHB) and Ganxin Region (GX).

3.4. Prospective Economic Profitability of Sweet Sorghum Bioethanol

The inputs and outputs of sweet sorghum bioethanol production in NEC, HHHB and GX were compared and analyzed (Figure 6). For the input side, it was obvious that the input of biomass logistics accounted for the largest input factor (54.4 to 57.8%) followed by stem bioethanol conversion (about 38.4 to 42.2%) (Figure 6a). The average input of sweet sorghum bioethanol production was highest for NEC (6832.7 USD/ha), followed by HHHB (6822.8 USD/ha) and lowest for GX (5595.3 USD/ha). The inputs of biomass logistics for the above three corresponding selected sites were 1.37 times, 1.21 times and 1.19 times that of the input of bioethanol conversion, respectively. For the output side, HHHB achieved the highest average output value of bioethanol production (4844.9 USD/ha), followed by NEC (4546.9 USD/ha), with the lowest value for GX (4006.8 USD/ha) (Figure 6b). In short, these results indicate that bioethanol production using sweet sorghum is not feasible or sustainable in any of the selected geographic areas from the standpoint of economic input and output. Based on the current industry technological status for conversion, the ranking of the theoretical net economic output values was GX (-1588.6 USD/ha) > HHHB (-1977.9 USD/ha) > NEC (-2285.8 USD/ha). Obviously, bioethanol production using sweet sorghum is still not feasible at the current levels of technology and bioethanol price in China.
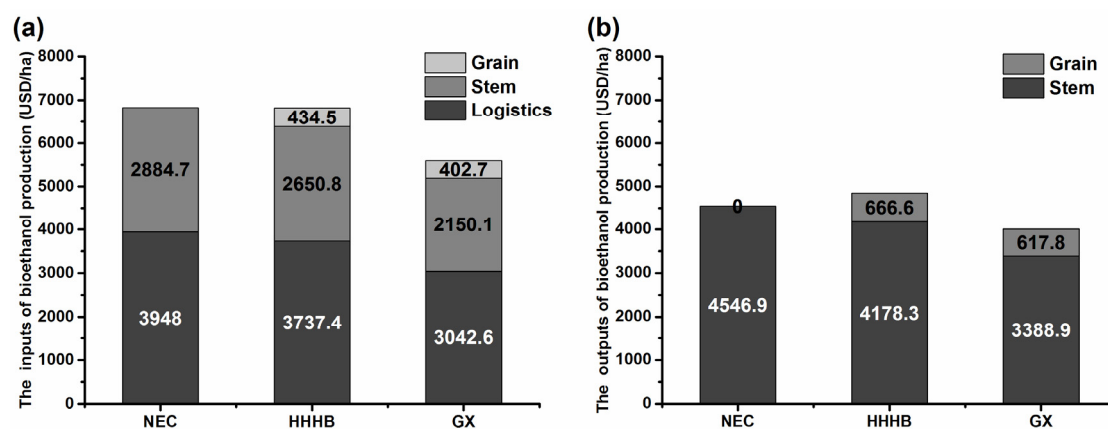

Figure 6. Economic inputs (**a**) and outputs (**b**) of sweet sorghum bioethanol production in Northeast China (NEC), Huang-Huai-Hai Basin (HHHB) and Ganxin Region (GX).

3.5. Sensitive Analysis of the Theoretical Net Economic Output under the Current Biomass Conversion Technology

As an ideal solution to solve dual challenges of energy and environmental security, numerous new conversion technologies have been developed for bioethanol production over the past two decades [65]. However, few studies have been conducted to evaluate the cost of bioethanol conversion, which could be considered a crucial factor for the development of the bioethanol industry [66]. Furthermore, logistical challenges that have led to poor financial return have also been reported as main barriers to using sweet sorghum as bioethanol feedstock [1]. Thus, two sensitivity analyses were conducted to identify the effects of bioethanol conversion and biomass logistics costs on the prospective economic profitability in the three selected regions analyzed in this study. Based on the theoretical calculation (Equations (5)–(8)), the initial values of inputs for bioethanol conversion were 2884.7 USD/ha, 3085.3 USD/ha and 2552.8 USD/ha in NEC, HHHB and GX, respectively. Notably, a similar ranking order was seen for biomass logistics inputs as for bioethanol conversion, with the ranking of locations as NEC (3948.0 USD/ha) > HHHB (3734.4 USD/ha) > GX (3042.6 USD/ha). In order to evaluate economic viability, the initial values of bioethanol conversion inputs (Figure 7a) or biomass logistics inputs (Figure 7b) were decreased by increments of 10% in three selected regions. Meanwhile, the other parameters remained unchanged.
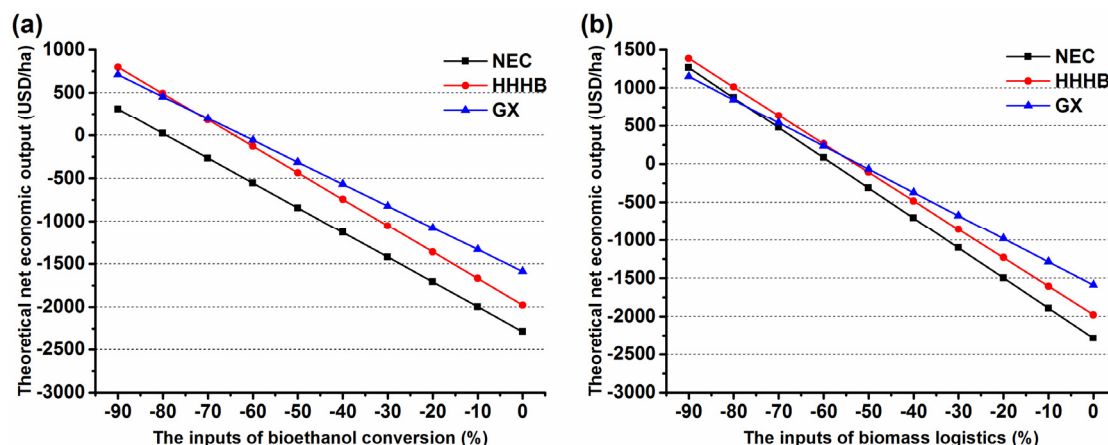

Figure 7. Sensitivity analysis of the theoretical net economic output of Advanced Solid-State Fermentation (ASSF) to assess the varying costs of bioethanol production (**a**) and biomass logistics (**b**).

Because of the cost structure presented earlier in Figure 6, it is obvious that proportionate biomass logistics cost reduction would lead to better prospective economic profitability than would proportionate reduction of bioethanol conversion cost. Ultimately, bioethanol production using sweet sorghum could achieve profitability in all of the selected areas when cost reduction of biomass logistics reached 60% (Figure 7a). In this case, HHHB would achieve the highest average net economic output (264.6 USD/ha), followed by GX (234.0 USD/ha), with the lowest value for NEC (83.0 USD/ha). In addition, net economic output would be ranked in the order of HHHB (1012.1 USD/ha) > NEC (872.6 USD/ha) > GX (845.5 USD/ha) when cost reduction of bioethanol logistics reached 80%. Nonetheless, these results still indicate that this process is far from economically feasible using the current biomass conversion processes in the selected regions, unless biomass conversion cost reductions reached 80% (Figure 7b). If such a large cost saving could be realized, the net economic outputs would be 490.38 USD/ha, 453.63 USD/ha and 21.94 USD/ha in HHHB, GX and NEC, respectively.

4. Discussion

Despite the fact that sweet sorghum is regarded as the most advantageous renewable bioenergy feedstock, its large-scale utilization for bioethanol production has not yet been realized in China [4].

Meanwhile, sustainability and economic feasibility studies of bioethanol production have mainly focused on a specific region or a single aspect of the bioethanol production process [33,35,66–73]. In addition, comprehensive assessment of sustainability and economic feasibility of sweet sorghum for bioethanol have been insufficient, even among various diverse areas across China.

In this study, the result from SPTM analysis first demonstrates that the NEC, GX and HHHB regions are the most suitable locations from a sorghum cultivation technological standpoint among all eight agricultural regions. Meanwhile, values for the degree of production maturity of the other five regions indicate they are all immature. This result is consistent with previous studies [3] that demonstrated that the NEC, HHHB and GX zones exhibited the highest potential for successful sweet sorghum cultivation for bioethanol production. Meanwhile, Li [27] suggested that the most promising of the unutilized land resources, after considering geographical condition for agricultural production, are Xinjiang and Inner-Mongolia, followed by the middle-lower Yangtze area and Loess Plateau and finally by Northeast China. In addition, Shi [74] reported that there were abundant forest resources and an advanced breeding research center in NEC, which was created to develop the bioenergy industry in coordination with use of forest residue and sweet sorghum as bioenergy feedstock. Therefore, these three areas, NEC, HHHB and GX, were recommended as the most feasible agricultural regions for large-scale sweet sorghum production.

As part of the sustainability analysis in this study, economic input and energy input of sweet sorghum production in GX were higher than those in NEC and HHHB; both higher inputs were primarily due to expensive labor costs and high labor intensity requirements during the field planting stage [33,35]. A previous study [75] had reported that economic efficiency of sweet sorghum planted on marginal land in Italy was superior to economic efficiency on fertile land, due to a lack of subsidies provided for sweet sorghum planting on the fertile land. In this study, great differences in economic output were observed between Wuyuan County and Gulang County in GX, mostly because the sweet sorghum variety in Gulang County is late-maturing and no-heading and has a higher stalk biomass; thus, stalk from Gulang County commands a higher price (57 USD/t) than from Wuyuan County (33 USD/t). Previous sweet sorghum life cycle assessment studies revealed that the GHGs were produced at their highest levels during the planting stage, as a result of N-fertilizer production and application, as well as the use of diesel fuel for farm machinery during this stage [22,71]. Other research [76] reported that in the North China Plain, using diversified crop rotation planting, the production of N fertilizer made the largest contribution to GHG emissions among all agricultural inputs, accounting for an average of 45% of emissions. The impact of N fertilizer application on total emissions, including direct N_2O emissions from N fertilizer application and indirect N_2O emissions from volatilized NH_3-N and NO_x-N and from nitrate leaching, accounted for an average 37% of total emissions. Another study [77] reported that the sizeable N fertilizer application amount and intensity in HHHB (especially in Shandong as a typical agricultural province) resulted in the markedly lower N fertilizer use efficiency than observed for NEC. No obvious differences were observed in soil and staple crop yields in two principal planting regions, HHHB and NEC. In this work, sustainability of sweet sorghum planting was highest in NEC but relatively lower in GX. In northwest China, including Xinjiang Province and the area north of the Great Wall, sweet sorghum has already been planted extensively. However, in these regions, the short frost-free period seriously restricts large-scale cultivation of sweet sorghum for bioenergy production. In the northwest area, the economic characteristics of bioenergy sweet sorghum are not stable and the temperature descends rapidly after harvest, which is favorable for storage but not for the crushing and fermentation of stalks requiring extra energy and economic inputs [78]. Besides concerns of energy efficiency, economic benefit and GHG emissions from sweet sorghum production, erratic weather, agricultural development and the resource potential of marginal land must also be considered before choosing a location for actual production.

This study evaluated an advanced conversion process based on current biomass feedstock supplies, beyond the state of bioethanol conversion technology in China, to evaluate the theoretical

productive potential and prospective economic profitability of sweet sorghum bioethanol in the three selected sites. Previous studies reported difficulties in comparing energy and water consumption for previously common liquid-state ethanol production methods [79]. Since then, due to its higher energy efficiency and lower water utilization [80], solid-state fermentation is now considered preferable to liquid-state fermentation. However, the absence of free water during solid-state fermentation leads to poor heating efficiency [61]. In the present study, the process that was considered was based on Advanced Solid-State Fermentation (ASSF) technology, which could overcome the aforementioned disadvantages [69,70]. As a result, the theoretical bioethanol potential was around 5228.7–6322.4 L/ha for the three selected agricultural regions if the ASSF technology were used there, which was higher than values obtained in previous studies [14,15,21,81]. Nevertheless, Figure 6 indicates that bioethanol production using sweet sorghum is still not economically feasible using processes currently used in the selected regions, due to high cost input of the bioethanol conversion and biomass logistics and the price commanded by the ethanol product.

As discussed in this paper, bioethanol production using sweet sorghum fell far short of achieving profitability using current technologies in China. One study [1] reported that sweet sorghum stalks were used inefficiently in China because they are grown in geographically dispersed areas with low energy density under the current system. Moreover, the main barrier to using biomass as a source of biofuel has been a logistics challenge rather than a technological one [1]. Consistent with the results of this study, the costs of biomass logistics were rather higher than bioethanol conversion inputs in all selected regions (Figure 6) mostly due to the lack of mechanization. One study indicated that the price of sweet sorghum logistics could decrease to 35.76 USD/t when the related system was well mechanized [1]. Hence, for bioenergy to succeed it appears most critical to increase the mechanization of the biomass logistics system. In tandem, new bioethanol production technologies should be developed to reduce total input costs of bioethanol production. It has been demonstrated [66] that a sustainable strategy of bioethanol production in China cannot be based only on sweet sorghum starch and juice; lignocellulosic bioethanol derived from sorghum bagasse could bring in more revenue per unit of feedstock than the current biomass mix. In addition, a recent study using a novel combined sweet sorghum bioethanol and power (CEP) model displayed a superior profitability than the currently used process [82]. From an economic sustainability standpoint, development of new technologies to convert all carbohydrates (including grain, juice and lignocellulose) in sweet sorghum into bioethanol and byproduct is urgently needed. Beyond this, genetic modification of energy crops has shown the promise to significantly enhance biomass yield and biofuel production, which could reduce the input of sweet sorghum logistics and bioethanol production [83]. So, genetic modification of sweet sorghum as a bioenergy crop also needs to be put on the agenda.

5. Conclusions

Sweet sorghum is becoming one of the most promising bioenergy crops in China. In this study, the technical feasibility of sweet sorghum production was assessed in eight agricultural regions in China using our high-throughput SPTM model. Next, comprehensive assessment of sustainability of sweet sorghum production (including net economic output, economic input-output ratio, net energy output, energy input-output ratio, greenhouse gas emissions and nitrogen use efficiency) was conducted for three selected typical agricultural regions, NEC, HHHB and GX. Results showed that the degree of technical maturity (DTM) of bioethanol production was relatively high in NEC (0.8066), followed by the value of GX (0.7531) and next by HHHB (0.6594); the DTM values of the other five regions were very immature and possessed degrees less than 0.5. From an economic point of view, bioethanol production from sweet sorghum is not feasible at China's current agricultural logistics and biofuel conversion stages of development. Thus, more efforts are needed to improve biomass logistics such as the dedicated equipment for mechanization, transport distance from depot, diesel price, transport distance from field side and baler rate to decrease total costs. Meanwhile, the development of new bioethanol production technologies also needs to be sped up.

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