Marginal land bioethanol production of sweet sorghum based on limited water resources in Northwest China

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Abstract: Sweet sorghum is considered a leading non-grain candidate for bioethanol production due to its low input requirement, good tolerance, high biomass potential, and high sugar content. However, insufficient studies have been conducted on the spatial distribution of sweet sorghum-based bioethanol production potential considering the water resources limitation. We presented a multi-factor analysis method not only considering terrain, meteorology, soil, and crop natural growth habits but also considering the local water resource to explore the available marginal land suitable for sweet sorghum cultivation and assess the bioethanol production potential in Northwest China. The results showed that 4.63×10^7 hm^2 available marginal land was suitable for sweet sorghum planting. Considering the constraint of local water resources, 2.76×10^6 hm^2 available marginal land was suitable for sweet sorghum planting, accounting for 4.7% of the total available marginal land. And 1.23×10^{10} L bioethanol could be produced on it. Moreover, for these districts under low water stress levels, 9.79×10^5 hm^2 available marginal land in Gannan Tibet AP and Longnan of Gansu and Hulun Buir of Inner Mongolia was considered a priority to develop sweet sorghum-based bioethanol, and 5.56×10^9 L bioethanol could be produced in these districts, which can satisfy the 1.54% biofuel goal for 2050 of China.

Keywords: bioethanol potential, marginal land, sweet sorghum, regional water stress levels, water resources limitation
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1 Introduction

With the growth of the world population and the soaring development of the global economy, the continuous consumption of fossil energy and the consequent environmental problems have attracted worldwide attention[1,2]. China is the world's most populous country, due to its fast-growing economy, which is the world's largest energy consumer and carbon emitter[3], accounting for around one-third of global CO_2 emissions[4]. China contributes half of the world's coal production and consumption[5], thus transitioning from fossil fuels to renewable energy can help mitigate CO_2 emissions to reach the carbon neutrality goal[6]. As a primary substitute for fossil energy and the most widely used type of renewable energy[7,8], bioenergy can reduce the consumption of fossil energy and ease environmental threats[9,10]. Compared to other bioenergy sources, energy crops have drawn more attention and played a crucial role in the national energy structure[11] because they are not only suitable for large-scale production and commercial applications[12] but also the primary source of newly added biofuel[13] in the coming decades. However, it is not encouraged to cultivate large-scale energy crops on existing arable land considering food security.

The exploitation and utilization of marginal land to cultivate energy crops can make up for the shortage of arable land and the shortage of fossil energy. In recent years, several publications are focusing on the potential and distribution of energy crops planted in the available marginal land[11,14-20]. Feng et al.[14] found that 60% of marginal lands in the Upper Mississippi River Basin were suitable for the growth of bio feedstock crops. Approximately 9×10^6 hm^2 of marginal land in Canada was suitable for biofuel crops and biofuel potential from marginal land could replace 28% of transportation gasoline[16]. And in China, a total of 1.35×10^8 t/a miscanthus biomass could be produced on 7.69×10^6 hm^2 of suitable marginal land, and this biomass could replace 6.46×10^7 t of standard coal annually[20]. To sum up, marginal land for the cultivation of energy crops has considerable renewable energy potential.

There are a large of marginal lands in northwest China[21]. Exploring its availability for energy crops could help mitigate the fossil fuel shortage[22]. However, bioenergy development was hindered by water resource scarcity and uneven spatial and temporal distribution. It is crucial to consider the water resource stress index for assessing the potential of marginal lands in this area. Sweet sorghum (*Sorghum bicolor* L. Moench) features its high biomass[23], rapid growth, wide adaptability[24], drought and salt tolerance[25,26], and juicy stalk containing abundant sugar[27], and relatively low production cost[28]. Sweet sorghum has potential on marginal land, and it is technically and economically feasible to use sweet sorghum as raw material to produce bioethanol[29]. Hence, it is identified as the most promising non-grain energy crop for bioethanol production, which could reduce competition with food crops on fertile cultivated land[30,31]. However, large-scale planting of energy crops will exacerbate the

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local water crises crisis. It is necessary to ascertain how much water and available marginal land could be used to develop sweet sorghum-based bioethanol production in northwest China. Therefore, the objectives of this study are to 1) explore the available marginal land distribution for sweet sorghum cultivation in arid and semi-arid regions using the multi-factor method; 2) estimate the bioethanol production potential of sweet sorghum considering water stress levels in each district.

2 Materials and methods

2.1 Research areas

The research areas include four provincial-level administrative districts (Xinjiang, Gansu, Ningxia, and Inner Mongolia), covering 46 administrative regions in Northwest China (32°11′N-53°23′N and 73°40′E-126°04′E), with an area of 3.34×10^8 km^2, accounting for 34.6% of China's total land (Figure 1).

Note: Numbers 1-46 represent the administrative divisions of the four provinces. Xinjiang: 1-Urumqi, 2-Kelamayi, 3-Tulufan, 4-Hami, 5-Changji Hui Autonomous Prefecture (Changji Hui AP), 6-Bortala Mongol AP, 7-Bayingol Mongolian AP, 8-Aksu Prefecture, 9-Kizilsu Kirghiz AP, 10-Kashgar Prefecture, 11-Hotan Prefecture, 12-Ili Kazak AP, 13-Tarbagatay Prefecture, 14-Altay Prefecture, 15-Shihezi; Gansu: 16-Jiuquan, 17-Jiayuguan, 18-Zhangye, 19-Jinchang, 20-Wuwei, 21-Lanzhou, 22-Baiyin, 23-Linxia Hui AP, 24-Dingxi, 25-Tianshui, 26-Pingliang, 27-Qingyang, 28-Gannan Tibet AP, 29-Longnan; Ningxia: 30-Yinchuan, 31-Shizuishan, 32-Wuzhong, 33-Guyuan, 34-Zhongwei; Inner Mongolia: 35-Hohhot, 36-Baotou, 37-Wuhai, 38-Chifeng, 39-Hunlun Buir, 40-Hinggan League, 41-Tongliao, 42-Holingola, 43-Ulanqab, 44-Ordos, 45-Bayan Nur, 46-Alxa League.

Figure 1 Location of research areas

2.2 Available marginal land (AML) for sweet sorghum cultivation

According to the Ministry of Agriculture and Rural Affairs of China, marginal land is not used for agriculture production, residential purposes, and other social uses[32]. Available marginal land for planting sweet sorghum was adopted based on the land use resources and the crop's natural growth habits.

2.2.1 Land use classification

Based on the land-use classification system of the Chinese Academy of Science[33], the national land-use types are divided into 6 classes and 25 subclasses. Within the research area, the marginal land resources include shrubland (system code: sc.22), sparse forest land, (sc.23) sparse grassland (sc.33), shoal (sc.44), bottomland (sc.45), sand land (sc.61), alkaline land (sc.63) and bare land (sc.65).

2.2.2 Crop growth habits

Based on the natural habit of sweet sorghum cultivation, the following conditions should be satisfied to obtain a considerable yield[21,34]: 1) terrain: slope less than 7° and altitude less than 1850 m; 2) soil: soil sand content <85% and 5.0<pH<8.5; 3) climate: the accumulated temperature above 10°C is greater than 2500°C.

2.3 Crop water requirement and water resources limitation

Bioenergy production consists of field production and bioethanol processing, and more than 90% of water was consumed during the field production[35], hence our study only focused on the water consumption for the field cultivation. According to the typical pilot field experiment at Shiyanghe Experimental Station of China Agricultural University, located in Wuwei, Gansu province of northwestern China (37°52'N, 102°50'E; altitude 1581 m), a total of 476 mm of water was required for sweet sorghum using the simplified water balance formula in which deep leakage, groundwater recharge, and surface runoff were neglected.

$$ET_C=P+I-\Delta S \tag{1}$$

where, ET_C, P, and I are crop water consumption (mm), rainfall (mm), and irrigation amount (mm) during the growth period, respectively; ΔS is the change in soil water content (mm) at the beginning and end of the growth period.

Nevertheless, the rainfall in most districts could not meet the crop water requirement, so irrigation was necessary to ensure the crop potential yield. And the amount of irrigation water was decided by the differential between the crop water demand and average annual rainfall during the growth stages.

In this study, the amount and distribution data of water resources are shown in administrative regions rather than a watershed. According to the United Nations' definition of regional water stress levels, the low, moderate, medium-high, and high water stress levels correspond to the percentages of total annual water withdrawals (TAWW) dividing total actual renewable water resources (TARWR), ranging from less than 10%, 10%-20%, 20%-40% to greater than 40%[35]. Accordingly, the available volume of water withdrawals (AVWW) for sweet sorghum cultivation should not exceed 40% considering the water resource sustainability[35]. Thus, the AVWW was calculated as:

$$\text{AVWW}=\text{TARWR}\times40\%-\text{TAWW} \tag{2}$$

2.4 Potential of bioethanol production from sweet sorghum considering the limited water resources

According to the above calculation of regional water stress levels in different districts, we excluded the districts where the water stress levels were beyond 40% on account of water resource sustainability. Based on the above constraints, the theoretical maximum planting area (TMPA) for sweet sorghum was calculated as:

$$\mathrm{TMPA}=\mathrm{AVWW}/(I/\varphi) \qquad (3)$$

where, φ is the effective coefficient of irrigation water utilization, and the value of 0.554 was used according to the China Water Resources Bulletin of 2018 from the Ministry of Water Resources of the People's Republic of China[36].

However, the TMPA may not represent the actual situation in some districts with abundant water resources and less available marginal land. Hence the actual maximum planting area (AMPA) was determined by Equation (4).

$$\mathrm{AMPA}=\begin{cases}\mathrm{TMPA},\ \mathrm{TMPA}<\mathrm{AMPA}\\ \mathrm{AMPA},\ \mathrm{TMPA}\geq\mathrm{AMPA}\end{cases} \qquad (4)$$

The maximum bioethanol yield (MBY) from sweet sorghum was determined by Equation (5).

$$\mathrm{MBY}=\mathrm{AMPA}\times\mathrm{FSY}\times\mathrm{JXR}\times\mathrm{B}\times0.585 \qquad (5)$$

where, FSY is the fresh stalk yield (103.09 t/hm^2), JXR is the juice extraction rate of sweet sorghum stalk (0.52), B is the stalk brix (18.12), and the data of FSY, JXR, B were from our typical field experiment at the Shiyanghe experimental Station in Wuwei, Gansu Province, China in 2019. At physiological maturity, 20 continuous plants without panicles and leaves were harvested to determine FSY. Then the juice of the stalk was extracted using a motor-operated 3-roller press. After juice extraction, the juice was weighed, and the Brix of the juice was determined by the handheld digital refractometer (ATAGO, PR-32, Co. Ltd., Tokyo, Japan). JXR was calculated as the ratio of juice weight to FSY. Thus, FSY per hectare was calculated from an individual stalk weight and the plant density (0.4 m for row space and 0.23 m for plant space) in a hectare. And 0.585 is the conversion factor obtained from Teetor et al.[37], which means 1 kg sugar could produce 0.585 L ethanol.

The actual regional water stress level (ARWSL) in each district was determined by Equation (6).

$$\mathrm{ARWSL}\ (\%)=(\mathrm{AMPA}\times I/\varphi+\mathrm{TAWW})/\mathrm{TARWR}\times100 \qquad (6)$$

2.5 Data collection and analysis

Two main data sources were used in this study: the first was used for the available marginal land assessment and the second was for determining the regional water stress levels.

The first data type included 1 km resolution grid data of meteorology, soils, slope, altitude, and land use. The daily meteorology data was from China Meteorology Administration (CMA). The slope and altitude data were derived from the Digital Elevation Model (DEM) of China. The 1:1000000 soil data were obtained from the China soil map based on Harmonized World Soil Database (HWSD). The land use data was provided by the Data Center for Resources and Environmental Sciences (RESDC) (http://www.resdc.cn).

The second data type was the Water Resources Bulletin of four provinces used for calculating the water stress levels, which contained a detailed list of water use for each administrative region. The Water Resources Bulletin data of Gansu, Ningxia, and Inner Mongolia was from 2014 to 2018, while that of Xinjiang was obtained from 2014 to 2016. All of the data and information used in this study are listed in Table 1.

Table 1 Application, resolution, and sources of the data and information used in this study

Application	Dataset/Information	Resolution	Sources
Available marginal land assessment	Soil data	1 km	Harmonized World Soil Database (HWSD）
	Slope & Altitude data	1 km	Data Center for Resources and Environmental Sciences (RESDC)
	Annual rainfall	1 km	China Meteorological Administration (CMA）
	Annual accumulated temperature	1 km	CMA
	Land use	1 km	RESDC
Water stress levels	Water Resource Bulletin	Prefecture level	Water Conservancy Department of each province

3 Results

3.1 Available marginal land distribution for sweet sorghum cultivation

Most districts could grow sweet sorghum in arid and semi-arid regions of northwest China (Figure 2). The results showed that the total available marginal land area was 4.63×10^7 hm^2, accounting for 15.3% of the entire research area. The available marginal land distributed in Xinjiang, Gansu, Inner Mongolia, and Ningxia were 2.28×10^7 hm^2, 4.58×10^6 hm^2, 1.79×10^7 hm^2, and 1.03×10^6 hm^2, respectively. Figure 3 presented that Alxa League in Inner Mongolia owned the largest available marginal land of 7.16×10^6 hm^2, and the Bayingol Mongolian AP in Xinjiang followed the second place with an area of 4.99×10^6 hm^2.

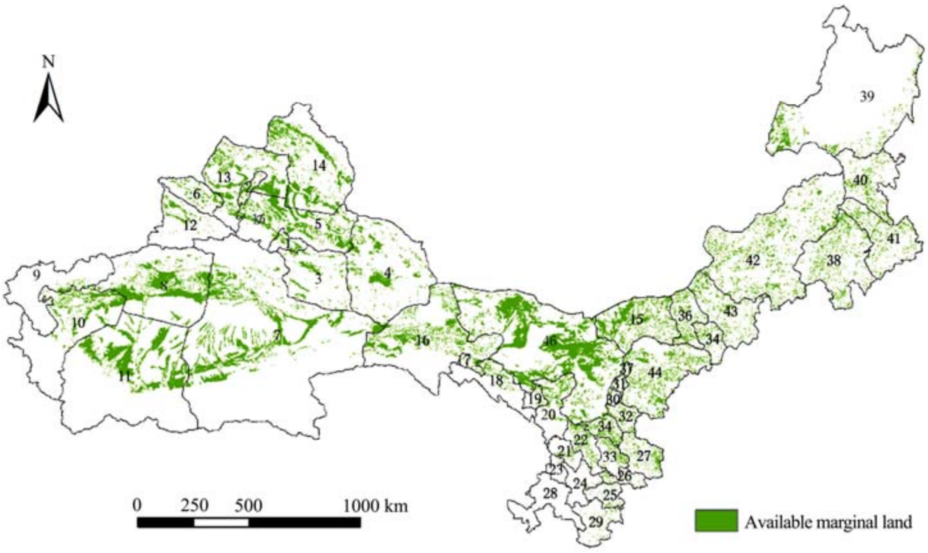


Figure 2 Distribution of available marginal land suitable for sweet sorghum cultivation

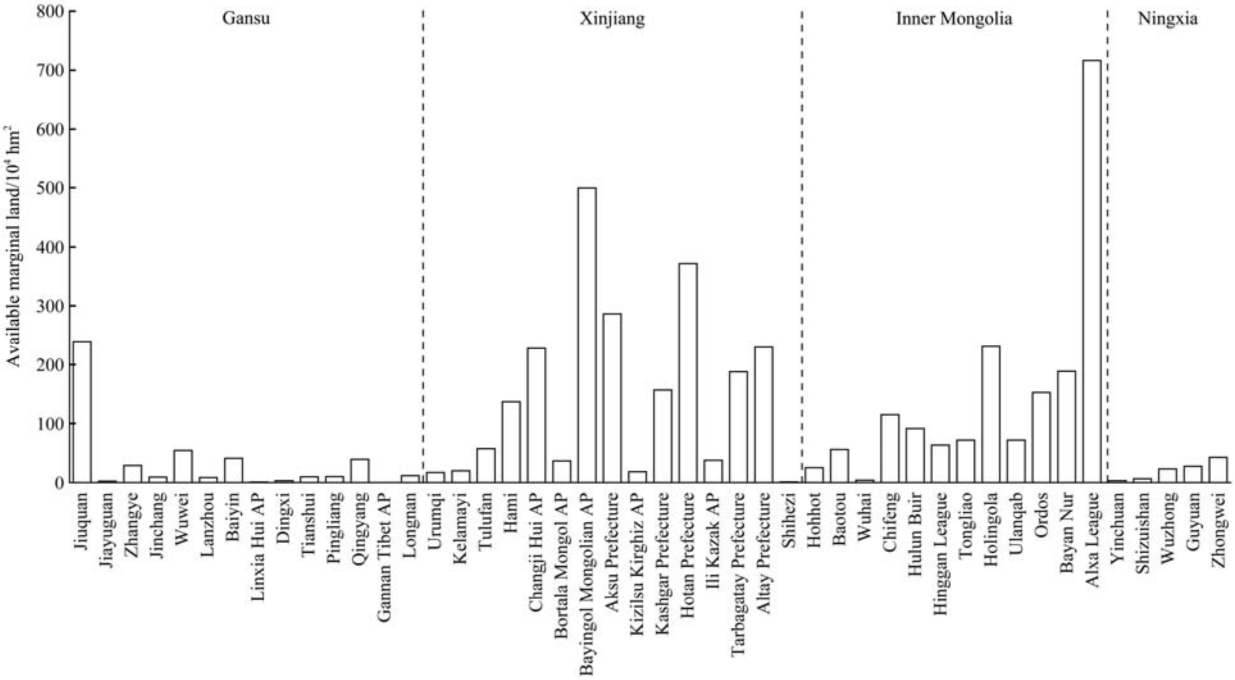


Figure 3 Areas of available marginal land suitable for sweet sorghum cultivation in each district

3.2 Water requirement for sweet sorghum cultivation and regional water stress levels

The rainfall in Tianshui, Pingliang, Gannan Tibet AP, and Longnan of Gansu province could meet the water demand of sweet sorghum cultivation, while the rest of the regions required extra irrigation water amount (Figure 4). Water requirements for sweet sorghum cultivation in Xinjiang, Inner Mongolia, and Ningxia varied from 228-427 mm, 51-381 mm, and 106-295 mm, respectively. Hotan Prefecture in Xinjiang required the greatest irrigation water demand (427 mm).

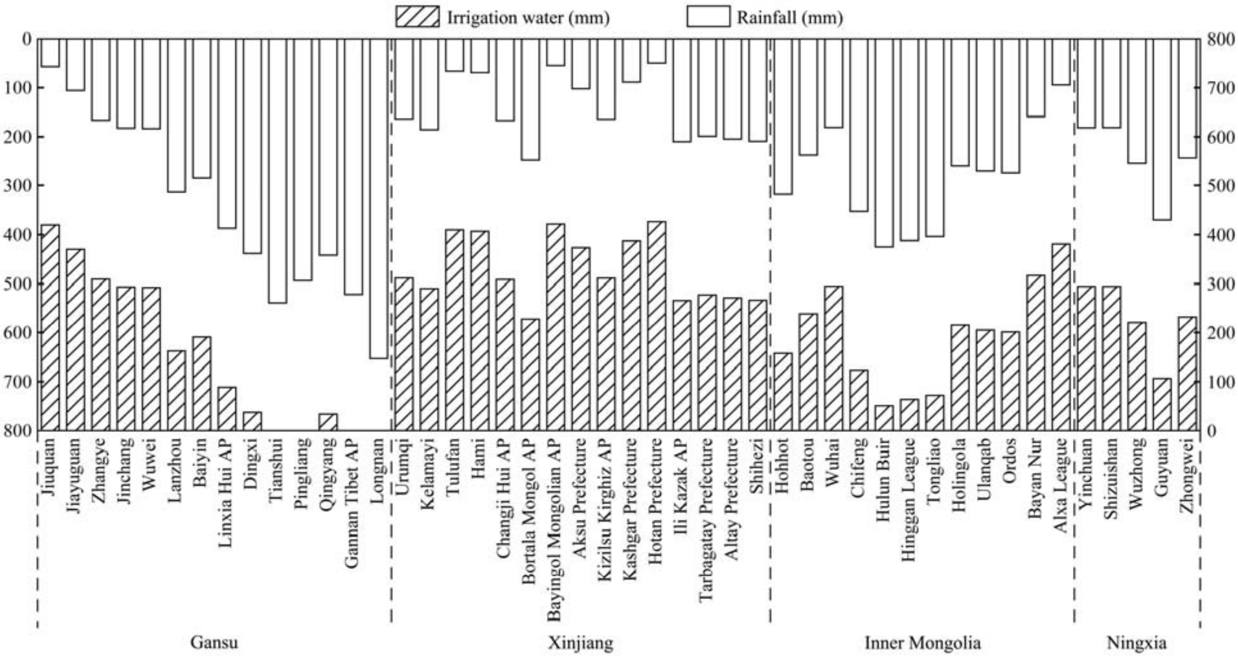


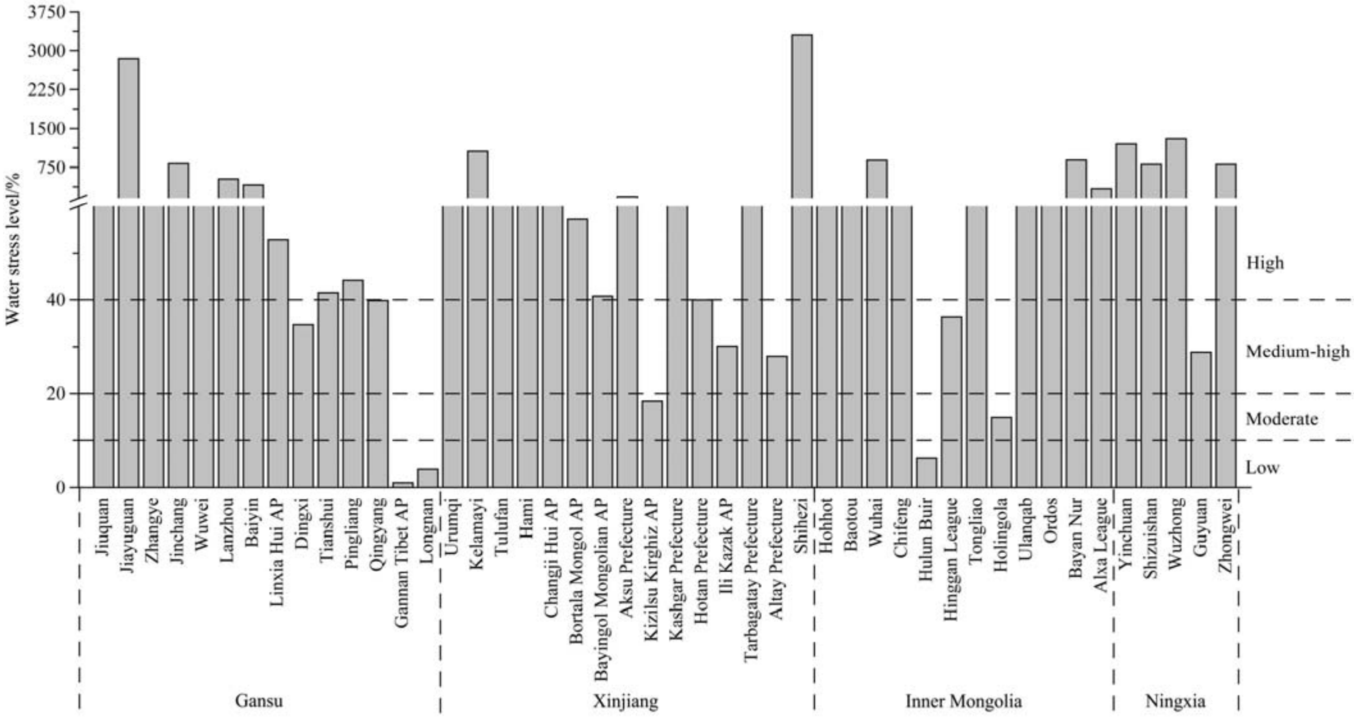
Figure 4 Rainfall and irrigation water in each district

Figure 5 shows that water stress levels in most regions were beyond high level, which was unsuitable for cultivating sweet sorghum. While the regional water stress levels of Dingxi, Qingyang, Gannan Tibet AP and Longnan of Gansu, Kizilsu Kirghiz AP, Hotan Prefecture, Ili Kazak AP, and Altay Prefecture of Xinjiang, Hulun Buir, Hinggan League and Holingola of Inner Mongolia, and Guyuan of Ningxia were lower than 40%. In these districts, Kizilsu Kirghiz AP and Holingola were in moderate water stress levels and Gannan Tibet AP, Longnan, and Hulun Buir were in low water stress levels.

3.3 AMPA and bioethanol potential considering the constraints of regional water resources

Considering the limited regional water resources, a total of AMPA reached 2.16×10^6 hm^2. The AMPAs in Gansu, Xinjiang, Inner Mongolia, and Ningxia were 9.75×10^4 hm^2, 8.19×10^5 hm^2, 1.22×10^6 hm^2, and 2.95×10^4 hm^2, respectively. Hulun Buir in Inner Mongolia reached a maximum area of 9.13×10^5 hm^2 for cultivating sweet sorghum, while Gannan Tibet AP only had the land of 4×10^2 hm^2 suitable for sweet sorghum cultivation.

In terms of the bioethanol production potential from the stalk of sweet sorghum, it could be seen that a total of 1.20×10^{10} L bioethanol could be produced if all the available land was used to grow sweet sorghum. The MBYs in Gansu, Xinjiang, Inner Mongolia, and Ningxia were 5.54×10^{8} L, 4.65×10^{9} L, 6.91×10^{9} L, and 1.68×10^{8} L. Consistent with the AMPA, the maximum and minimum bioethanol production appeared at the Hulun Buir of Inner Mongolia and Gannan Tibet AP of Gansu, respectively (Table 2).



Note: The low (<10%), moderate (10%-20%), medium-high (20%-40%), and high water stress levels (>40%) correspond to the percentages of total annual water withdrawals (TAWW) dividing total actual renewable water resources (TARWR)

Figure 5 Regional water stress levels in each district

Table 2 TMPA, AML, AMPA, MBY, and AWSL of the districts below 40% water stress level

Province	District	TMPA /×10^4 hm^2	AML /×10^4 hm^2	AMPA /×10^4 hm^2	MBY /×10^8 L	AWSL /%
Gansu	Dingxi	8.47	3.08	3.08	1.75	35.84
	Qingyang	0.14	39.18	0.14	0.08	40.00
	Gannan Tibet AP	0.04	0.08	0.04	0.03	0.98
	Longnan	6.49	11.71	6.49	3.69	3.91
	Sum	15.14	54.05	9.75	5.55	
Xinjiang	Kizilsu Kirghiz AP	25.25	18.40	18.40	10.46	27.13
	Hotan Prefecture	0.08	370.95	0.08	0.04	40.00
	Ili Kazak AP	33.98	37.61	33.98	19.31	36.18
	Altay Prefecture	29.40	229.68	29.40	16.70	40.00
	Sum	88.71	656.64	81.86	46.51	
Inner Mongolia	Hulun Buir	977.44	91.33	91.33	51.90	7.91
	Hinggan League	10.97	63.35	10.97	6.23	40.00
	Holingola	19.33	230.77	19.33	10.99	40.00
	Sum	1007.74	385.45	121.63	69.12	
Ningxia	Guyuan	2.95	27.52	2.95	1.68	40.00
	Sum	1114.54	1123.66	216.19	122.86	

Note: TMPA: Theoretical maximum planting area; AML: Available marginal land; AMPA: Actual maximum planting area; MBY: The maximum bioethanol yield; AWSL: Actual water stress levels.

4 Discussion

4.1 Available marginal land for sweet sorghum cultivation and potential bioethanol yield

Developing cleaner biofuel from non-food bioenergy crops such as sweet sorghum on marginal land plays a crucial role in the national energy structure, which could alleviate the conflict between food security and fossil energy depletion[38]. Regional water availability affects the crop planting area availability[39]. Due to the water resource limitation, a large of marginal land resources in northwestern China was not exploited[40]. The regional water resource stress levels were not considered in previous researches on exploring the available marginal land[18,20,21], which leads to a much larger land area compared with our study. As several studies emphasized the importance of taking regional specifics into account when assessing the water demand for bioethanol production[41,42], we selected suitable land based not only on the irrigation requirement of sweet sorghum but also on available local water resources. Thus, our result showed that 2.16×10^{6} hm^{2} of available marginal land was suitable for sweet sorghum cultivation considering the regional water stress levels, accounting for 4.7% of the available marginal land in northwest China. If all the available marginal land was used for t bioethanol production, it will produce 1.23×10^{10} L/a bioethanol, which could satisfy 3.41% of China's biofuel development goal for 2050[43].

4.2 Data uncertainties

Firstly, since this research was based on the yield per hectare through a typical pilot field experiment, the yield of sweet sorghum cultivated in different districts could result in uncertainties of potential production. Secondly, the data of 1-km resolution would influence the results. Finally, even though we considered the local water stress levels and the effective coefficient of irrigation water utilization for sweet sorghum cultivation, the impacts of cost-benefit[16], energy efficiency[44], transportation[45], policy guidance, and other factors were not taken into consideration for the conversion of sweet sorghum into bioethanol. Therefore, future studies are needed to focus on sweet sorghum cultivation on the marginal land. Also, advanced technologies for bioethanol production and policy support for growers are needed to accelerate sweet sorghum bioethanol production.

4.3 Suggestions for the development of sweet sorghum in northwest China

In this study, the theoretical potentials of sweet sorghum-based bioethanol production on marginal land were assessed. The distribution of water resources in Northwest China is uneven spatially and temporally, it is the better choice to consider the available local water resources when the available marginal land was used to cultivate the energy crops. Bioethanol production was considered a potential priority in Gannan Tibet AP and Longnan in Gansu and Hulun Buir in Inner Mongolia due to their low regional water stress level, where 9.79×10^5 hm^2 available marginal land was used to cultivate the sweet sorghum, harvesting 5.56×10^9 L of bioethanol which could meet the 2020 goal of bioethanol production of 5.07×10^9 L. For the medium-term development goal of bioethanol, planting sweet sorghum in the districts where the regional water stress levels are below 40% is a good choice. Additionally, it is beneficial for the arid and semi-arid regions to develop energy crops-based bioethanol by adopting precise and water-saving irrigation technologies to achieve considerable yield while reducing the water demand for energy crops[46].

The novelty of this study is that a new integrated method was proposed to assess the distribution and bioethanol potential of sweet sorghum. This method applies not only to northwest China but also to other regions of the world when the marginal land resource is used to develop sweet sorghum-based bioethanol production. The results presented in this study could provide a bioethanol potential map of sweet sorghum for the policymaker to develop sweet sorghum-based bioenergy in northwest China.

5 Conclusions

In this study, a multi-factor method was used that not only considered the terrain, meteorology, soil, and the crop's natural growth habits but also took the local regional water stress levels into consideration to explore the available marginal land suitable for sweet sorghum cultivation and to assess the bioethanol potential in northwest China. The available marginal land for sweet sorghum cultivation is 4.63×10^7 hm^2, producing 1.23×10^{10} L of ethanol. When constraint of regional water stress level was taken into consideration, only 2.76×10^6 hm^2 of available marginal land is suitable for sweet sorghum cultivation, accounting for 4.7% of the total available marginal land, and a total of 1.23×10^{10} L ethanol can be produced. Furthermore, Gannan Tibet AP and Longnan in Gansu and Hulun Buir in Inner Mongolia, whose water stress levels were 0.98%, 3.91%, and 7.91% respectively, were suggested as priority development districts for sweet sorghum-based bioethanol.

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