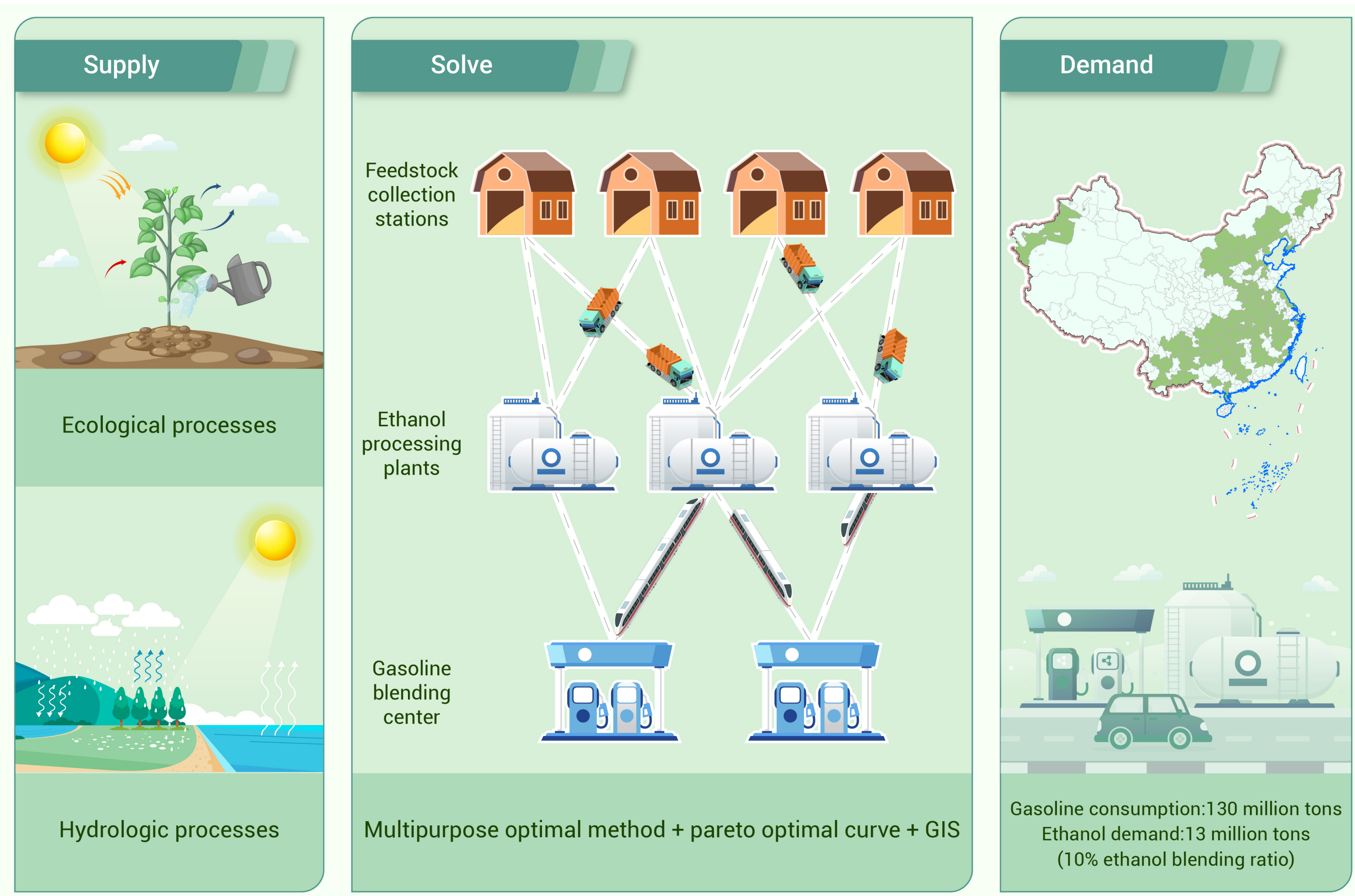
ARTICLE

Optimization and benefit analysis of the supply chain for sweet sorghum bioenergy production in China

Dong Jiang,[1,2,3,7] Ting Peng,[4,7] Ziqiang Bu,[1,2] Jingying Fu,[1,2,5,*] Gang Lin,[1,2,3] and Wanqiu Zhang[6]
*Correspondence: fujy@igsnrr.ac.cn

Received: February 8, 2024; Accepted: August 9, 2024; Published Online: August 13, 2024; https://doi.org/10.59717/j.xinn-energy.2024.100038

GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Bio-liquid fuels are one of the effective ways to alleviate energy shortages and reduce greenhouse gas emissions.
- Aboveground biomass of sweet sorghum was 595.39 million tons in China, which could meet the demand of promoting automobile ethanol gasoline in China.
- Feedstock collection station, ethanol processing plant, gasoline blending center are the three basic units of ethanol supply chain.
- Establishing large ethanol plants near the Hu Huanyong Line helps to reduce costs.

ARTICLE

Optimization and benefit analysis of the supply chain for sweet sorghum bioenergy production in China

Dong Jiang,[1,2,3,7] Ting Peng,[4,7] Ziqiang Bu,[1,2] Jingying Fu,[1,2,5,*] Gang Lin,[1,2,3] and Wanqiu Zhang[6]

[1]Institute of Geographic Science and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[2]College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China

[3]Key Laboratory of Coupling Processes and Effects of Natural Resource Elements, Ministry of Natural Resources, Beijing 100055, China

[4]China Telecom Corporation Beidou Technology Innovation Center, Wuhan 430064, China

[5]Key Laboratory of Coupling Processes and Effects of Natural Resource Elements, Ministry of Natural Resources, Beijing 100812, China

[6]College of Geoscience and Surveying Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China

[7]These authors contributed equally

*Correspondence: fujy@igsnrr.ac.cn

Received: February 8, 2024; Accepted: August 9, 2024; Published Online: August 13, 2024; https://doi.org/10.59717/j.xinn-energy.2024.100038

Citation: Jiang D., Peng T., Bu Z., et al., (2024). Optimization and benefit analysis of the supply chain for sweet sorghum bioenergy production in China. The Innovation Energy **1**(3): 100038.

Bio-liquid fuel is one of the effective ways to alleviate energy shortages and reduce greenhouse gas emissions. Sweet sorghum, as an energy crop used in fuel ethanol production, has enormous potential for development. However, due to seasonality, vulnerability, and logistical scheduling costs during transportation, the sweet sorghum ethanol supply chain faces significant difficulties and challenges in its development. To address the research gap, this paper proposes a multi-objective sustainable supply chain optimization model for Chinese sweet sorghum bioenergy based on mixed-integer linear programming. In this framework, the crop growth process model is first spatially extended to obtain the feedstock sources of the sweet sorghum ethanol supply chain. Then a site selection model for the feedstock collection stations and ethanol processing plants is constructed based on the geographic information system (GIS) to determine the candidate locations of the basic units of the sweet sorghum ethanol supply chain. Finally, a multi-objective supply chain optimization model based on the mixed-integer linear programming methodology is created to achieve the sweet sorghum ethanol supply chain layout and optimization at the national level. This framework takes into account the fuel ethanol market demand in China and the current state of the sweet sorghum ethanol supply chain industry, achieving national-level layout and optimization of the sweet sorghum ethanol supply chain. The total aboveground biomass (dry weight) of sweet sorghum on marginal land in China can be converted into approximately 37.212 million tons of fuel ethanol production, meeting the requirement to promote a nationwide 10% substitution rate for automotive ethanol gasoline. The lowest-cost supply chain layout scheme suggests establishing large ethanol processing plants near the Hu Huanyong Line, as this area benefits from abundant sweet sorghum yield on marginal lands and lower east-west direction transportation costs. However, the lowest carbon emission supply chain layout scheme recommends reducing the raw material supply area and increasing the ethanol transportation route to lower carbon emissions. The results of the sensitivity analyses indicate that lowering feedstock production and increasing ethanol demand increases the overall cost and carbon emissions of the sweet sorghum ethanol supply chain, while using rail transportation methods, increasing feedstock production, and decreasing ethanol demand reduces costs and carbon emissions.

INTRODUCTION

The challenges of global warming and environmental problems are becoming increasingly serious, so renewable energy alternatives to fossil fuels have attracted great interest. The development of biomass energy not only solves environmental problems, but also brings socio-economic benefits.[1,2] For example, considering the dual factors of food security and production efficiency, an effective way to prepare feedstock for fuel ethanol production is to grow sweet sorghum (a cellulosic second-generation energy plant) on the marginal land.[3] However, few studies have simultaneously considered the questions of bioenergy production and supply under the multiple objectives described above. Considering the importance of biomass energy development in China's response to climate change and transition to sustainable energy, the socio-economic benefits of biomass energy development must be emphasized in addition to environmental considerations.[4,5]

Although China's fuel ethanol industry has realized rapid development from scratch in recent years, due to the agricultural mode, market environment, technological limitations, and policy changes, development of the biomass energy industry represented by biofuel ethanol faces many challenges in terms of economic and social operations. For example, on the economic side, feedstock acquisition costs are high.[6] China's sources of biomass feedstock are wide, but they are too dispersed to be collected and utilized effectively. In the pursuit of high efficiency, biomass projects rush to acquire starchy raw materials such as stale grains and cassava, thus intensifying competition among enterprises and leading to higher feedstock prices for raw materials. Socially, the fuel ethanol supply chain network structure is irrational, lacking coordination among stakeholders at various levels, which impedes scientific decision making regarding supplier selection, site location, route, and technology choices.[7] Therefore, a thorough analysis of key issues in the fuel ethanol supply chain and exploration of a scientific development mode for China's fuel ethanol supply chain is urgently needed.

Supply chain optimization models are widely used in healthcare, food, energy and other fields.[8-11] The used models can be generally divided into deterministic models, stochastic models, and hybrid models.[12] Deterministic models assume that all model parameters are known and fixed, which can be further divided into single-objective and multi-objective models, then into linear programming, mixed-integer linear programming, and so on.[13,14] When solving supply chain problems using deterministic models, the methods are flexible and varied, with mixed-integer linear programming being widely used. This approach involves quantitatively simulating the real environment, establishing objective functions, adding realistic constraints, and using computers to find the best decision-making scheme, which helps to make more scientific and rational decisions. Recent research on deterministic models mainly focuses on the expression of model uncertainty and model acceleration. For example, Goli et al. proposed a mathematical formulation and solution method for the uncertainty in the organ transplant supply chain problem to optimize the organ transplant supply chain under transport time uncertainty.[15] In addition, Goli et al. investigated the energy awareness of non-instantaneous flow shop scheduling and batch sizes using an improved novel meta-heuristic algorithm and proposed a new hybrid integer programming algorithm, which provides Pareto optimal solutions in a shorter period of time and speeds up the solution considerably compared to traditional algorithms such as the Epsilon constraint.[16] Goli et al. also used the accelerated Benders decomposition (ABD) algorithm to address the complexity of the model in order to find the optimal strategy when designing a closed-loop supply chain network for dairy products.[17] Currently, blockchain concepts are also widely used in supply chain optimization problems, such as Alireza et al. designed a blockchain-enabled closed-loop supply chain, considering the role of the product portfolio,[18] the framework helps supply chain managers to significantly reduce the decision-making errors in physical and financial flows.

And with the continuous progress of supply chain optimization models, the research of biomass fuel supply chain is also developing at a faster speed. Kostin et al. combined life cycle assessment with a multi-objective mixed-integer linear programming model based on the minimization of costs and environmental impacts of the bioethanol–sugar supply chain and applied the model to the sugarcane industry in Argentina.[19] Huang et al. developed a mixed-integer linear programming model that uses spatial, agricultural, techno-economic, and environmental data for multi-objective optimization of the renewable aviation fuel supply chain system.[20] Galanopoulos et al. combined a supply chain network mixed-integer linear programming model developed using the AIMMS software with a process plant simulation model developed using Aspen Plus (R) to optimize the biorefinery network. The final results are used for economic value and environmental impact analysis of the entire biorefinery network.[21] Ahranjani et al. proposed a mixed-integer linear programming model to address the design and planning of a multi-feedstock lignocellulosic bioethanol supply chain network, where a hybrid robust stochastic probabilistic planning approach was introduced to cope with the uncertainty of a priori knowledge and the risk of supply chain disruption.[22] And Akbarian-Saravi et al. proposed an integrated decision support tool that combines artificial neural networks, mathematical modeling and solution methods. In this tool, a multi-objective mixed integer linear programming model was developed to optimize the supply chain structure and a neural network model was used to forecast the bioethanol demand.[23] However, for the fuel ethanol supply chain, the location of raw material collection stations and ethanol processing plants are crucial factors directly affecting the entire system's operation. Existing optimization research has mostly analyzed individual links of the supply chain (e.g., biomass supply, storage, factory/warehouse location, transportation) to reduce costs, with little focus on the full life cycle optimization of the entire process from biomass collection, processing, and transportation to distribution. Therefore, it is crucial to comprehensively assess the production potential of sweet sorghum on marginal land and utilize it in the construction of supply chain optimization models.

Therefore, this thesis proposes a framework for the scientific layout of China's biomass ethanol industry. Based on the distribution of sweet sorghum biomass resources, the spatial analysis method of GIS and the supply chain network integration and optimization capability of mixed integer linear programming model are brought into play to answer the questions of how to lay out the facilities of China's biomass ethanol industry, as well as how to establish the optimal upstream and downstream supply chain transportation relationship to maximize the economic and environmental benefits of the supply chain. China's fuel ethanol supply chain generally faces problems such as a single supply mode, irrational structure, and poor risk resistance. By constructing biomass supply modes, new ideas can be provided for the development of the supply chain. Optimizing the scientific layout of supply chain facilities and logistics can maximize supply chain benefits, enhance the interests of farmers, ethanol companies, and users, break through the development bottlenecks of the fuel ethanol supply chain, and provide a scientific basis for development of the fuel ethanol industry.

MATERIALS AND METHODS

This study proposes a research framework for life cycle optimization of the sweet sorghum ethanol supply chain in China, which integrates crop growth process simulation, site selection allocation, and supply chain optimization methods (Figure S6). First, using marginal land as the system boundary, a crop production process model is used to conduct a kilometer-grid scale simulation of the production potential of sweet sorghum. Second, considering facility characteristics and location influencing factors, a site selection model based on GIS methods is constructed to determine the optimal candidate locations for key facilities in the supply chain. Finally, using the life cycle analysis method as the research framework, an optimization model for the sweet sorghum ethanol supply chain is constructed to analyze and achieve the dual objectives of economic cost and carbon emissions. Through comprehensive comparative analysis of different scenarios, an optimal layout plan for the sweet sorghum ethanol supply chain in China can be proposed.

Step 1: Obtain the yield of sweet sorghum as the raw material for the sweet sorghum ethanol supply chain (see Supplementary Materials). 1) Obtain the spatial distribution of marginal land energy crop resources: Based on China's land-use data and various conditions such as policy regulations, ecological protection constraints, livestock development constraints, and the scale of energy crop development, the spatial distribution data of marginal land suitable for the large-scale development of energy crops in China can be obtained.[24] 2) Obtain homogeneous land units using spatial information technology: The spatial distribution map of marginal land with data required by the DSSAT model, such as meteorological data, soil data, and topographic data, is overlaid and analyzed to obtain homogeneous land units for use as input to the DSSAT model.[25] 3) Optimize the crop model parameters: Sensitivity analysis of the crop model parameters is conducted based on the reference literature, expert reports, and on-site investigation data of energy crop test bases, followed by optimization of the crop variety parameters using the Generalized Likelihood Uncertainty Estimation (GLUE) model. 4) Predict energy crop biomass: The biomass of energy crops is predicted using the spatial extended DSSAT model.

Step 2: Determine the candidate locations of the transportation network and basic units of the biofuel supply chain (see Supplementary Materials). 1) Determine the candidate locations of raw material collection stations: Using the Thiessen polygon method, the locations, quantity, and capacity of candidate raw material collection stations are determined. 2) Determine the candidate locations of ethanol processing plants: Based on county-level administrative boundaries, railway and road transport networks, water body distribution, urban–rural distribution, population size, existing factory locations, and biomass production distribution data, the candidate locations for ethanol processing plants are determined using buffer analysis and regional statistical analysis methods. 3) Obtain the primary transportation network of the fuel ethanol supply chain: Network analysis methods in spatial information technology combined with the actual road network are used to calculate the shortest paths between potential facility locations, which serve as the primary transportation network between various facility sites of the fuel ethanol supply chain.

Step 3: Overall layout optimization of the sweet sorghum ethanol supply chain (see Supplementary Materials). Based on the data required for optimization such as biomass production distribution, candidate locations of supply chain facilities, biomass procurement costs, unit transportation costs, and the construction and operating costs of each facility, a mixed-integer linear programming model is constructed to optimize the fuel ethanol supply chain. The model provides an optimal solution for supply chain network design, ethanol plant scale, quantity and location, supply schemes, and logistics scheduling decisions. Sensitivity analysis is conducted on key parameters of the model to identify the main factors affecting the cost and carbon emission objectives of the ethanol supply chain, and to comprehensively evaluate the strengths and weaknesses of the sweet sorghum ethanol supply chain.

See Supplemental Information for more detail on the materials and methods used in this study.

RESULTS

Spatial distribution of sweet sorghum yield

Combining the growth characteristics of sweet sorghum, the multi-factor comprehensive evaluation method (see Supplementary Materials) and the geographic dataset made from the growth conditions shown as Table 1 and the multi-source data shown as Table 2 are used to obtain the quantity and spatial distribution of land resources suitable for planting high-biomass sweet sorghum as a non-grain raw material for fuel ethanol in China (Figure 1A). The marginal land area suitable for planting sweet sorghum in China is determined to be approximately 339,000 square kilometers.

By coupling GIS technology with the DSSAT model, this study obtains the spatial distribution data of the sweet sorghum growth conditions (Figure 1B). The total aboveground dry weight of sweet sorghum on marginal land is estimated to be approximately 595.39 million tons. Assuming a sweet sorghum stem-to-ethanol conversion rate of 16:1, the estimated total ethanol production that can be converted from sweet sorghum is 37.212 million tons. According to the China Energy Statistical Yearbook, China's apparent gasoline consumption in 2022 is approximately 133.1256 million tons,[26] and the fuel ethanol demand calculated based on a 10% ethanol blending ratio is 13 million tons. Therefore, the sweet sorghum yield on marginal land can meet the raw material supply demand for promoting the nationwide implementa-

Table 1. Growth conditions of sweet sorghum.

Index class	Specific parameter	unit	Threshold value
landform	slope	°	<25
soil	PH(H_2O)	-	5.0-8.5
	Soil organic matter content	%	>1.5
	Sand content of soil	%	≤85
	Soil depth	cm	≥30
temperature	Minimum temperature in April-June	°C	>15
	≥10°CAccumulated temperature	°C	≥1500
water	Annual precipitation	mm	≥200

Table 2. Data required for extraction of marginal land of sweet sorghum.

Data	Measure	Format	Time	Sources	Remark
Land use data	1km×1km	Raster	2018	Resource and Environmental Science Data Center (https://www.resdc.cn/)	There are 6 primary classifications and 25 secondary classifications
DEM	1km×1km	Raster	—	SRTM (https://www.earthdata.nasa.gov/sensors/srtm)	Obtain slope data
Meteorological data	1km×1km	Raster	2018	China Meteorological Administration (https://weather.cma.cn/)	Including temperature, precipitation data, etc
Soil data	1km×1km	Raster	—	Resource and Environmental Science Data Center (https://www.resdc.cn/)	Including soil thickness and organic matter content
Nature reserve data	1:100,000	Shape file	2018	Resource and Environmental Science Data Center (https://www.resdc.cn/)	—

tion of a 10% substitution rate for ethanol gasoline.

The Extended Fourier Amplitude Sensitivity Test (EFAST) is used to analyze the parameter sensitivity of the DSSAT model.[27] The value range and distribution of 20 crop variety parameters are used as input, and Monte Carlo sampling is performed 5000 times to obtain a parameter sample set. The generated parameter sample set is input into the configuration file of the DSSAT-Sorghum[28] model using the Python language, resulting in 5000 model output results. The output results are then input into the model processing module, and the EFAST method is used to calculate the sensitivity analysis results of each parameter, obtaining the top five parameters with the highest global sensitivity index in the sweet sorghum crop variety parameters of the DSSAT model: TBASE (base temperature for growth), RUE (radiation use efficiency), KCAN (canopy extinction coefficient), P1 (accumulated temperature from emergence to juvenile stage), and GDDE (accumulated temperature required for emergence at each seed depth in centimeters).

Feedstock collection station and ethanol processing plant site selection simulation

Optimizing the simulation of the fuel ethanol supply chain require initial determination of candidate locations for raw material collection stations and ethanol processing plants. In the sweet sorghum ethanol supply chain, the raw material collection stations are primarily responsible for the acquisition, pre-processing, and storage of surrounding biomass resources. Selecting suitable locations can reduce the initial costs associated with raw material transportation and management. In this study, the division of raw material collection stations and their respective acquisition areas have to meet two conditions: first, there should only be one collection station within each collection area, second, the distance from raw material supply points within the collection area should be closest to the collection station, which ensures that all raw materials within the collection area are transported to the nearest collection station, minimizing the transportation costs. Based on the similarity in the raw material collection process at collection stations, a location selection model based on Thiessen polygons is constructed (see Supplementary Materials). The results of the division of raw material supply areas for collection stations with quantities of 50, 100, 150, and 200 are simulated sequentially (Figure 2), serving as alternative options for supply chain optimization. To obtain the optimal division scheme for raw material supply areas, sensitivity analysis is conducted on the number of collection stations. Through the established multi-objective optimization model considering economic and environmental factors, the economic and environmental effects of different configurations of collection station quantities on the sweet sorghum fuel ethanol supply chain are evaluated (Figure S1). Among the different configurations of collection station quantities, the total cost and total carbon emissions of the sweet sorghum fuel ethanol supply chain are minimized when the number of collection stations is 100. Therefore, the division results with 100 collection stations are considered as the optimal scheme for the division of raw material supply areas in this study.

After determining the locations of the raw material collection stations, the next step involves determining the locations of the ethanol processing plants. As the central link in the fuel ethanol supply chain, the number and locations of the ethanol processing plants are crucial for minimizing logistics and transportation costs. In terms of location factors for ethanol processing plants, this study mainly considers two aspects. First, priority is given to areas near water sources (e.g., rivers, lakes) and abundant biomass raw material supply, in order to minimize variable operating costs and raw material transportation management cost. Second, locations near railways, towns, areas with dense road networks, and high population densities are preferred, while avoiding locations near existing ethanol processing plants. Convenient transportation is essential for plant site selection, as it facilitates the transportation and distribution of biomass raw materials and ethanol products. Higher population density helps to ensure a certain potential consumer market and labor supply for the supply chain. To avoid competition for biomass raw materials, factory site selection should be as dispersed as possible. Locations with road network density greater than 0.2 km/km^2, biomass raw material yields greater than 15,000 kg/ha, and population density greater than 1,000 $people/km^2$ are identified through regional statistical analysis. A buffer zone of 3 km is established around railway transportation networks and water bodies, and locations within this buffer zone are selected. A buffer zone of 50 km is created around existing ethanol processing plants, and locations within this buffer zone are excluded. Finally, the selected candidate locations are converted into point elements, which are then considered as candidate positions for ethanol processing plants in the subsequent optimization model.

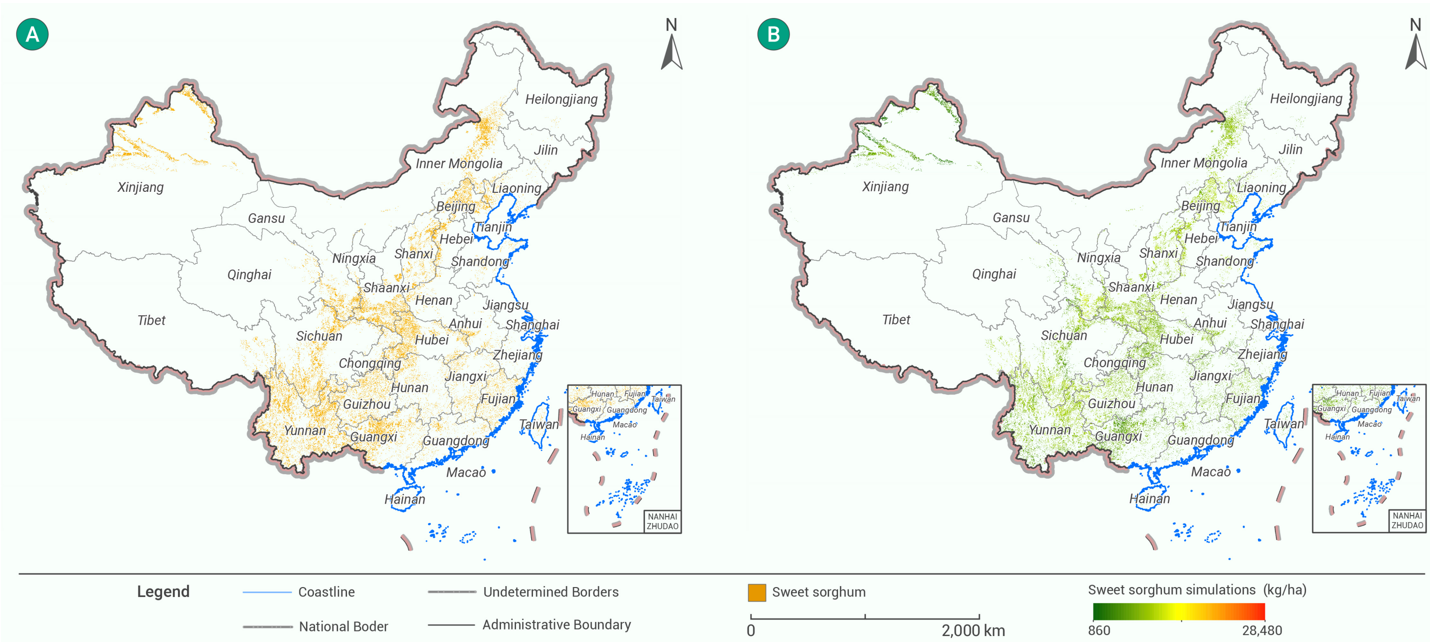


Figure 1. Assessment of sweet sorghum production potential (A) Spatial distribution of marginal land suitable for planting sweet sorghum in China, (B) Spatial distribution of simulation results of aboveground biomass (dry weight) of sweet sorghum in China. Validation of the DSSAT model sweet sorghum variety parameters based on field trial data shows that the linear regression coefficients of the measured and simulated yields of the two sweet sorghum varieties are greater than 0.75, indicating that the model simulation results are reasonable.

Optimization layout and comprehensive benefits of sweet sorghum ethanol supply chain

In order to minimize the annual total cost and carbon emissions of the three-tier supply chain of "raw material collection station–ethanol processing plant–gasoline blending center", a fuel ethanol supply chain optimization model is constructed based on mixed integer linear programming methods (see Supplementary Materials), so as to select the optimal number, location, and capacity of raw material collection stations and ethanol processing plants, as well as to determine the most effective transportation flow pattern within the system. Based on the optimal configuration of 100 candidate raw material collection stations, filtered candidate ethanol processing plant configurations, and road transport networks, the model aims to meet the demand for automotive fuel ethanol in various prefecture-level cities nationwide. This study considers the network structure of the fuel ethanol supply chain under both road and railway transportation modes (see Figure S2. Fuel Ethanol Supply Chain Network Structure). Under the road transport mode, material transport between the three types of facilities is considered to be conducted using trucks. Under the railway transport mode, because the railway network does not cover every prefecture-level city, the distance from the ethanol processing plant to each prefecture-level city's gasoline blending center for railway transportation is not available. Therefore, a transportation transfer station is established between the ethanol processing plant and the gasoline blending center, with material transport between the raw material collection station, ethanol processing plant, and the transportation transfer station being carried out by train, and material transport between the transportation transfer station and the gasoline blending center being conducted by road.

The economic optimization results indicates that the annual minimum cost of operating the sweet sorghum fuel ethanol supply chain is 211.253 billion yuan (Table 3). The cost of raw material planting and production is the most important component, accounting for 49% (Figure 3E). The results of the cost-minimized supply chain network optimization are shown in Figure 3A & B. In the optimal supply network from the raw material collection station to the ethanol processing plant, a total of 85 raw material supply areas are selected, with the supply range varying from 148,326 to 19,043,455 tons. Additionally, 31 ethanol processing plant locations are selected, with ethanol plant capacities ranging from 500,000 to 2,411,987 tons. A total of 96 raw material transport routes from the raw material collection station to the ethanol processing plant have been generated, with material flow ranging from 21,774 to 19,043,455 tons. The capacities of the ethanol processing plant and raw material transport flow are classified into small, medium, and large levels using the natural breakpoint method.

In the optimal supply network from the ethanol processing plant to the gasoline blending center, the fuel ethanol demand of the 344 prefecture-level cities ranges from 1505 to 590,320 tons, classified into small, medium, and large levels too. A total of 374 ethanol transport routes from the ethanol processing plant to the gasoline blending center are generated, with material flow ranging from 1585 to 485,894 tons, which are differentiated by color based on different starting points. In this scheme, large and medium raw material supply areas are mainly distributed near the Hu Huanyong Line (a geographical boundary in China),[29] while small raw material supply areas are distributed in the southeastern region, which is consistent with the distribution of marginal land suitable for sweet sorghum in China. Similarly, large and medium ethanol processing plants are also located near the Hu Huanyong Line, indicating that building raw material collection stations and ethanol processing plants in regions abundant in sweet sorghum biomass is a beneficial measure for cost reduction. The transportation routes from the raw material collection station to the ethanol processing plant reflect a clear principle of proximity, while the transportation network from the ethanol processing plant to the gasoline blending center shows a noticeable trend of supplying from the southwest to the central-eastern regions. Additionally, due to the transportation distance and sweet sorghum yield distribution, a radial supply network is evident in Xinjiang and the northeastern regions.

The environmental optimization results indicate that the annual minimum carbon emissions of the sweet sorghum fuel ethanol supply chain operation amount to 887.81 billion kilograms (Table 3). The carbon emissions during the ethanol production stage are the most significant component, accounting for 74%, followed by those of the transportation stage (18%) and sweet sorghum planting stage (Figure 3F). The optimized results of the supply chain network with the lowest carbon emissions are shown in Figure 3C & D. In the optimal supply network from the raw material collection station to the ethanol processing plant, a total of 83 raw material supply areas are selected, with the supply range varying 166,589 to 19,043,455 tons. Additionally, 31 ethanol processing plant locations are selected, with ethanol plant capacities ranging from 500,000 to 2,411,987 tons. A total of 95 raw material transport routes from the raw material collection stations to the ethanol processing plants are generated, with material flow ranging from 166,589 to 19,043,455 tons. In the optimal supply network from the ethanol processing plants to the gasoline

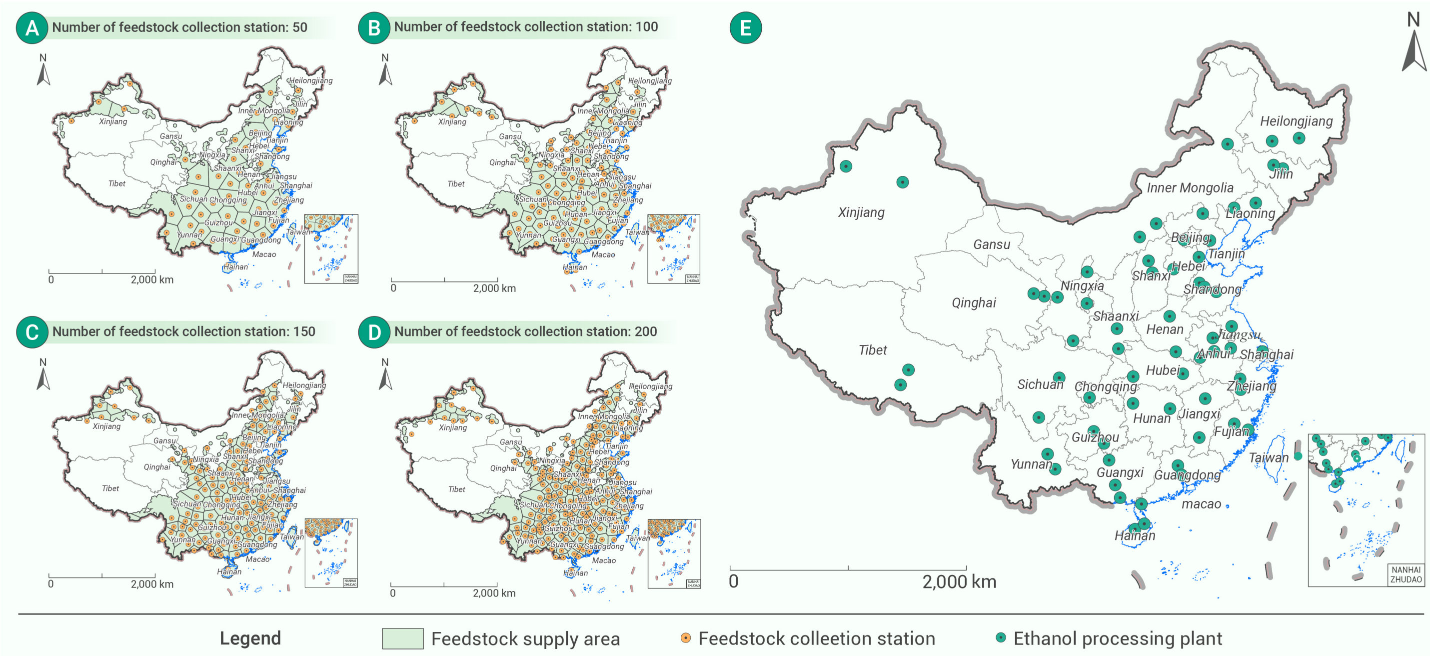


Figure 2. Sweet sorghum feedstock collection station and ethanol processing plant site selection simulation The division results of the raw material supply area are obtained for the number of feedstock collection stations: (A) 50, (B) 100, (C) 150, and (D) 200, (E) Distribution of candidate ethanol processing plant locations.

blending centers, 528 ethanol transport routes are generated, with material flow ranging from 208 to 485,894 tons.

Figure 3G shows the Pareto optimal curve, balancing economic and environmental objectives. The annual operating total cost and total carbon emissions of the sweet sorghum fuel ethanol supply chain network are two conflicting objective values, with the total cost decreasing as carbon emissions increase. Conversely, a reduction in carbon emissions is accompanied by an increase in the total cost. From the perspective of economic and environmental objective function values, the lowest economic cost is 211.253 billion yuan, with the drawback of emitting an additional 3 million tons of CO_2 beyond the lowest carbon emissions. Meanwhile, the lowest carbon emissions are 88.781 billion kg, with the cost being an additional expenditure of 9 million yuan beyond the lowest cost (Table 3). Compared to the supply chain simulation results with the lowest cost, the reduction in carbon emissions in the supply chain simulation with the lowest carbon emissions is due to the reduction of 2 raw material supply areas and the addition of 154 ethanol transport routes (Table 3). The reason for the increase in costs, on one hand, is that the amounts for different capacity levels of ethanol plants have changed, with the number of large ethanol plants increasing from 6 to 7 (Table 3), leading to an overall increase in the cost of ethanol plants. On the other hand, 154 ethanol transport routes are added, resulting in an increase in transportation costs.

DISCUSSION

While sweet sorghum is considered the most suitable energy plant for nationwide promotion in China, the vast geographical area of China also offers potential for the development of various other energy crops. Therefore, it is necessary to analyze the comparative benefits of fuel ethanol supply chains under the multi-feedstock supply mode. In this mode, five different types of energy plants are considered: sugar-based feedstock (sweet sorghum and sugarcane), starch-based feedstock (cassava), and cellulose-based feedstock (reed canary grass and switchgrass). These five types of raw material have significant differences in terms of suitable development areas, potential yields, planting costs, ethanol conversion costs, and carbon emissions intensity at different stages.

Figure S4 shows the results of the dual-objective supply chain optimization model under different feedstock supply modes. From Figure S4A, it can be seen that the Pareto curve under the sweet sorghum supply mode is clustered at one point, while the Pareto optimal curve under the multi-feedstock supply mode presents a large span of values, forming a distinct curve, indicating that the economic and environmental optimization results under the sweet sorghum supply mode do not differ greatly. Meanwhile, the economic and environmental optimization results under the multi-feedstock supply mode present significant differences and a large fluctuation space. In terms of values, the carbon emissions under the sweet sorghum supply mode are much higher than those under the multi-feedstock supply mode, indicating that the environmental benefits of the sweet sorghum ethanol supply chain are inferior to those of the multi-feedstock supply chain. The total cost under the sweet sorghum supply mode is at a medium to low level compared to the multi-feedstock supply mode, indicating that the overall operating cost of the sweet sorghum ethanol supply chain is relatively stable, while the cost fluctuation of the multi-feedstock supply chain is large.

From Figure S4B and Figure S4C, it can be seen that the total cost under both supply modes decreases as the total carbon emissions increase. When considering only the economic optimization, the total cost and carbon emissions under the sweet sorghum supply mode are higher than those under the multi-feedstock supply mode. Meanwhile, when considering only the environmental objective optimization, the total cost under the sweet sorghum supply mode is lower than that under the multi-feedstock supply mode, while the total carbon emissions are still higher than the latter, indicating that the multi-feedstock supply mode performs better in terms of environmental benefits, but has a certain degree of uncertainty in terms of economic benefits (Table S4). This is attributed to the multi-feedstock supply mode considers the use of a mature starch-based feedstock, cassava, which has the advantages of low cost, high utilization, and low emissions in ethanol production from energy plants, thus making a certain contribution to the reduction of the total cost and carbon emissions of the entire supply chain. Secondly, in terms of the number of facilities and transportation routes, in the multi-feedstock supply mode, the number of raw material collection stations (reduced by 30 compared to the sweet sorghum supply mode) and ethanol processing plants (reduced by 10 compared to the sweet sorghum supply mode) both significantly decrease, indicating a tendency to adopt a centralized configuration in the optimized multi-feedstock supply mode, which is also conducive to the reduction in the total cost (Table S4). In terms of the number of transportation routes, the multi-feedstock supply mode has fewer transportation routes than the sweet sorghum supply mode, also due to the centralized configuration of the facility sites.

From the perspective of the spatial distribution of the optimized supply

Table 3. Model results under economic and environmental optimization.

		Economic optimization	Environmental optimization
Total cost (billions of dollars)		2112.53	2112.62
Total carbon emissions (billion kg CO_2)		887.84	887.81
Number of raw material collection stations (units)		85	83
Different capacity levels number of facilities	small	54	52
	middle	25	25
	large	6	6
Number of ethanol processing plants (units)		31	31
Different capacity levels number of facilities	small	16	17
	middle	9	7
	large	6	7
Transportation paths from feedstock collection stations to ethanol processing plants (bars)		96	95
Transportation routes from feedstock collection stations to gasoline blending centers (bars)		374	528

chain network , when considering the lowest cost alone, the feedstock supply area and ethanol processing plants selected by the multi-feedstock fuel ethanol supply chain are concentrated in the area south of the Qinling Mountains-Huaihe River Line in China (Figure S5A and Figure S5B). The purpose is to meet the national ethanol demand with the least number of facilities (53 collection stations, 17 ethanol plants) and transportation routes (59 from collection stations to ethanol plants, 354 from ethanol plants to gasoline blending centers). It can be seen that, under the conditions of diverse feedstock types, a centralized configuration can achieve the maximum cost reduction. When considering only the lowest carbon emissions, the multi-feedstock fuel ethanol supply chain strategy mainly focuses on the southern regions, selecting feedstock collection stations and ethanol processing plants in areas such as Xinjiang, Ningxia, Shanxi, Hebei, and Tianjin (Figure S5C and Figure S5D). Although such spatial distribution reduces carbon emissions, it led to a significant increase in costs (379.63 billion yuan higher than the cost under economic optimization alone). Compared to the multi-feedstock fuel ethanol supply chain, the sweet sorghum fuel ethanol supply chain has a greater number of raw material collection stations, with 32 and 25 more in the economic and environmental optimization results, respectively. This is partly due to the limited yield of sweet sorghum requiring more feedstock supply areas, and also indicates that the sweet sorghum ethanol supply chain may require the use of more marginal land resources.

The simulation results obtained in various existing ethanol supply chain studies in China are provided in Table S5. A comparison of the obtained simulation results with those of other studies demonstrates that the unit cost of the marginal land ethanol supply chain in this paper is higher than that in other studies, and the unit carbon emissions are higher than those of Liu et al., but more consistent with the study of Tian et al.[30,31] The reasons for the difference include the following three aspects: inconsistent system boundaries of the models (the system boundary used in this paper being broader), differences in estimation methods and parameters, and differences in research objects and scope, with the research object of this paper being more diverse and the scope being broader. Therefore, the research results of this paper can be considered reasonably reliable.

Nevertheless, there are still some limitations in this study.

1.The innovation of the optimization algorithm needs to be improved. In this study, there is a lack of certainty and uncertainty assessment work in building the supply chain optimization model, as well as a lack of improvement of the optimization algorithm itself, such as not using heuristic algorithms or other optimization algorithms for multi-objective solving and thus increasing the solution speed of the optimization algorithm.[15,16] In future research, we will explore the incorporation of blockchain technology to describe and optimize the flow of funds in the biomass fuel supply chain.[18]

2. Consideration of uncertainty factors is still not perfect. The biomass industry, including the fuel ethanol industry, is a weak industry in China, the industrial organizational structure and operation mode are still immature,[32] and the industrial development is vulnerable to climate change, regional differences, traffic conditions, policy changes and other factors, so in actual production, the sweet sorghum ethanol supply chain network faces a variety of uncertainties. However, in this paper, only three factors (transportation mode, raw material production and ethanol demand) are selected for sensitivity analysis, more factors should be paid attention to other factors contributing to uncertainty in future research.

3.The difficulties and challenges of landing realistic scenarios are not fully considered. This study is a full estimation of the marginal land of sweet sorghum that can be planted as an energy crop, and therefore accounts for a relatively high percentage compared to the area of cultivated land (the total cultivated land of the country in 2022 is 1,275,800 square kilometers, and the marginal land area of sweet sorghum estimated in this paper is 339,000 square kilometers, which accounts for 26.57%, or about 1/4 of the area of cultivated land). This raises the challenge of whether China is sufficiently committed to utilizing such a vast area of land for bioenergy production while climate extremes become increasingly fierce.[33] It has been heavily explored over the past few decades, mainly for food, oil and cash crop production, so there is significant resistance to converting crop production to bioenergy sweet sorghum production. Therefore, future research will assess the suitability of marginal lands for energy crop production to make the results more relevant.

In addition, we will consider the economic benefit analysis such as market price, net profit, return on investment ratio and other indicators in the model in the subsequent research, and transform the constraints of science and technology innovation, policy, socio-economic conditions and industrial model into social benefits (employment population, agricultural structure, probability of policy support), energy benefits (energy input-output ratio), etc., in order to make the optimization results of the biomass fuel ethanol supply chain more practically instructive.

Sensitivity analysis is essential for proving the rationality of supply chains. In the supply chain network, the transportation mode, raw material production, and ethanol demand present fluctuations, which can affect the entire supply chain. This study conducts a sensitivity analysis regarding the impacts of these three parameters on the annual operating costs and carbon emissions of the sweet sorghum fuel ethanol supply chain. The comparison of transportation modes considers the contrast between road and rail transportation modes, while sensitivity related raw material production is compared at four levels: −10%, 0, +10%, and +20%. Sensitivity related ethanol demand is also compared at four levels: −20%, -10%, 0, +10%. The optimized results of the above seven scenarios and the basic research scenario (using the road transportation mode, marginal land sorghum production simulated based on the crop production process model, and fuel ethanol demand estimated based on the car ownership data in the statistical yearbook) are

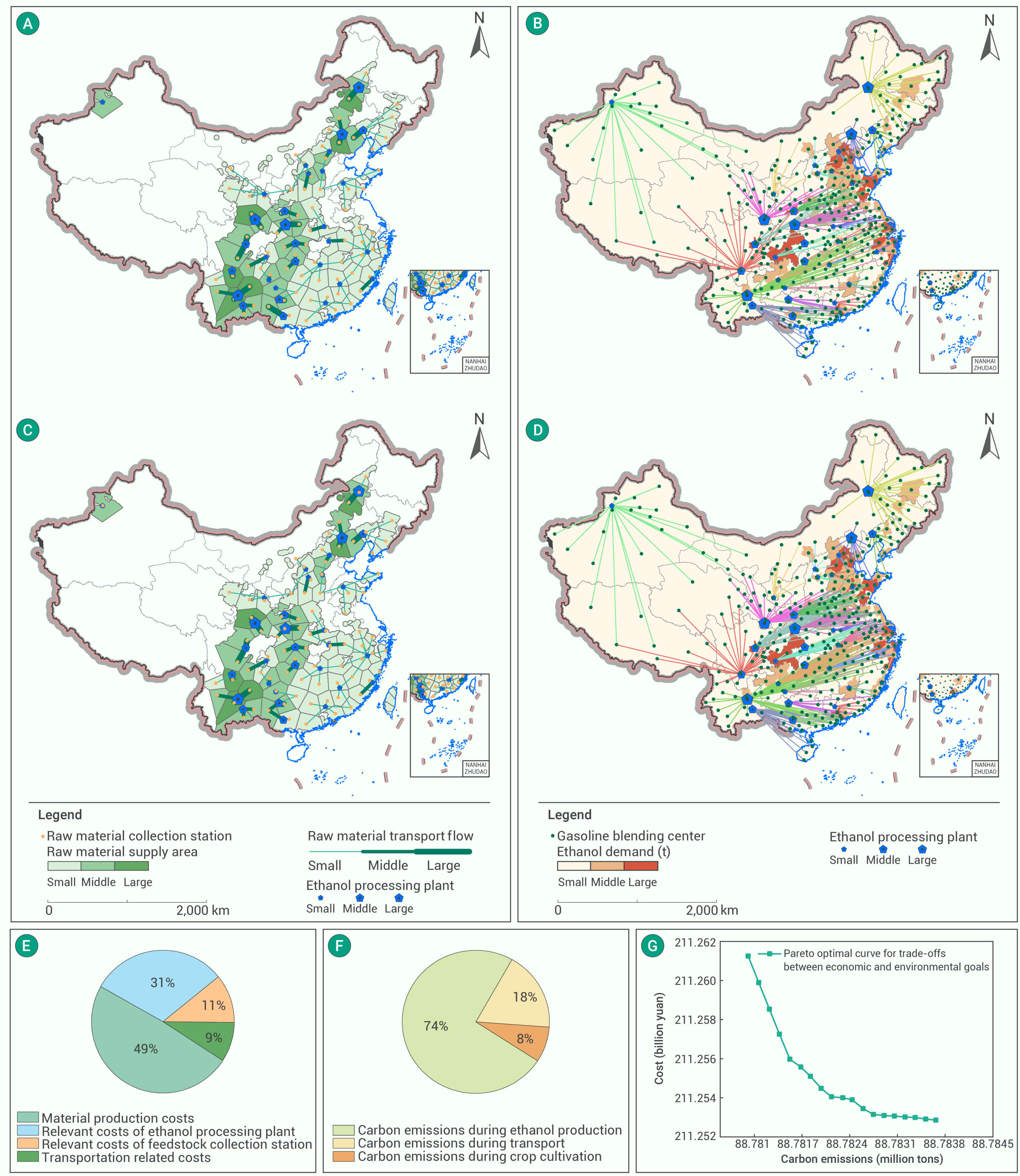


Figure 3. Optimization Layout and Comprehensive Benefits of Sweet Sorghum Ethanol Supply Chain (A) Optimal supply network from raw material collection station to ethanol processing plant under economic optimization. (B) Optimal supply chain from ethanol processing plant to distribution centers under economic optimization. (C) Optimal supply network from raw material collection station to ethanol processing plant under environmental optimization. (D) Optimal supply chain from ethanol processing plant to distribution centers under environmental optimization. (E) Minimum production cost decomposition under economic optimization. (F) Minimum carbon emissions decomposition under environmental optimization. (G) Pareto optimal curve for trade-offs between economic and environmental goals.

compared and analyzed. Figure 4A shows the Pareto optimal curves under different scenarios, with two scenarios having economic and environmental objective function values higher than the base scenario, and five scenarios having economic and environmental objective function values lower than the

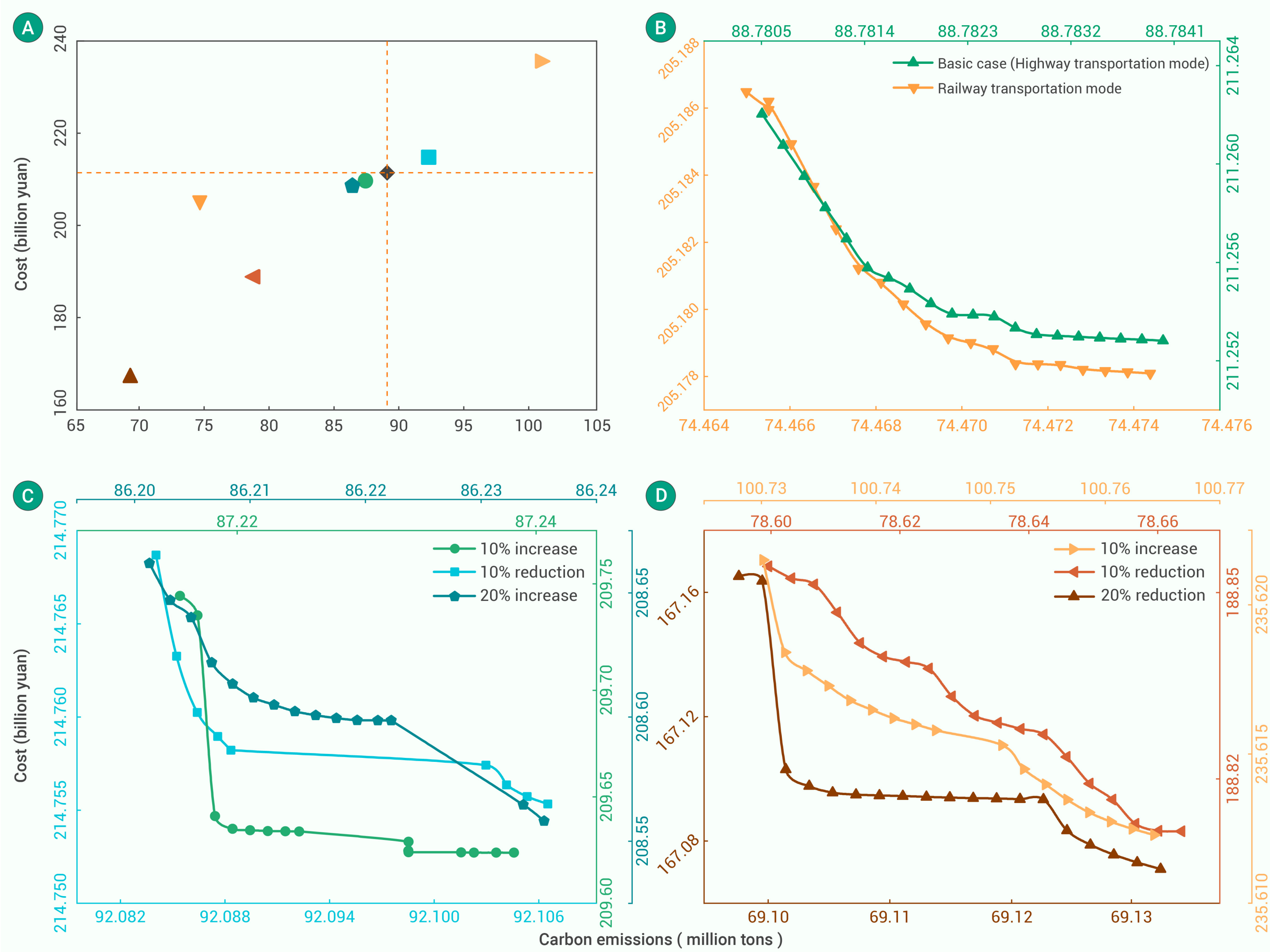


Figure 4. Sensitivity analysis of key parameters (A) Pareto optimal curve under different scenarios. (B) Pareto optimal curve of different transportation modes. (C) Pareto optimal curve of different raw material output levels. (D) Pareto optimal curve of different ethanol demand levels.

base scenario.

The annual operating costs and carbon emissions of the supply chain are also sensitive to different modes of transportation. Therefore, a supply chain network structure for road and rail transportation modes is constructed to reflect and study the impact of transportation modes on supply chain optimization. The results obtained from the dual-objective supply chain optimization models for different transportation modes are shown in Figure 4B. The trend of changes in the Pareto optimal curves under the two transportation modes is consistent, with both total costs decreasing as the total carbon emissions increase, but the reduction in costs slows down as the total carbon emissions increase. From the optimization results, it can be seen that the economic and environmental objective function values of the railway transportation mode are superior to those of the road transportation mode. The lowest economic cost under the railway transportation mode is 60.755 billion yuan lower than that for the road transportation mode, and the lowest carbon emissions value is 143.099 billion kg lower than that for the road transportation mode (Table S1).

The main cause for this observation is that the supply area of the supply chain covers prefecture-level cities across the country, resulting in large transportation volumes and long distances. Therefore, the railway transportation mode, which has high transportation capacity and relatively low transportation costs, performs well in the optimization results. In terms of the number of facilities and transportation routes, the selection of raw material collection stations and ethanol processing plants don't differ significantly, as it aligns with the consistency between raw material supply and ethanol demand. The quantity of material flow from the raw material collection stations to the ethanol processing plants is also relatively similar.

However, there are significant differences in the transportation network between ethanol processing plants and gasoline distribution centers. Due to the introduction of transportation transfer stations (one per province) in the railway transportation mode, the transportation network from ethanol processing plants to gasoline distribution centers is divided into two segments: railway transportation from ethanol processing plants to the transportation transfer stations in each province, and highway transportation from the transfer stations to the prefecture-level gasoline distribution centers within each province. During the transportation process from ethanol processing plants to the transfer stations, a large volume of transportation and long distances are involved, fully utilizing the advantages of railway transportation. Meanwhile, during the transportation process from the transfer stations to the prefecture-level gasoline distribution centers, the transportation volume is smaller and the distances are shorter, in alignment with the characteristics of highway transportation. Figure S3 represents the optimal supply network for economic and environmental optimization under the railway transportation mode. It can be observed that the transportation network from ethanol processing plants to gasoline distribution centers is sparser under the railway transportation mode, indicating a significant reduction in transportation distances.

The decision regarding raw material production, as well as the location, quantity, and capacity of raw material collection stations, is closely related to the production of raw materials and the associated costs and carbon emissions during the planting and collection stages. Therefore, the impact of raw material production on supply chain optimization is analyzed by setting the raw material production at −10%, +10%, or +20% (when the raw material production is decreased by 20%, the model is unsolvable due to insufficient raw material production, therefore, this level is not used). The results obtained from the dual-objective supply chain optimization model at different raw material production levels are shown in Figure 4C. From the model optimization results, it can be seen that, when the raw material production increases (+10% and +20%), the economic and environmental objective function values of the model are superior to those in the base scenario. When the raw material production decreases (−10%), the economic and environmental objective values of the model are higher than those in the base scenario (Table S2). This is attributed to ample raw materials provide more room for selecting the location and quantity of raw material supply areas.

From the number of settings and transportation paths, with an increase in raw material production, the number of raw material collection stations decreases, and the transportation paths from the raw material collection stations to the ethanol plants also decrease. This indicates that, with sufficient raw material production, the location of raw material collection stations tends to become concentrated. Choosing fewer but higher-capacity raw material collection stations can utilize economies of scale to reduce the costs incurred in the raw material collection phase. The number of ethanol plants remains stable while the raw material production increases. This indicates, on one hand, that the operational costs of ethanol plants are relatively high, the principle of centralized configuration cannot reduce costs. On the other hand, this can be attributed to the fact that the next station for the ethanol plants is the regional gasoline distribution centers across the country, the locations and demand levels of which remain unchanged. Thus, the impact on the decision regarding the location and number of ethanol plants is relatively small.

The demand for ethanol is closely related to the decision regarding the location, quantity, and capacity of ethanol processing plants which, in turn, affects the location, quantity, and biomass quality of raw material supply areas, thus impacting the costs and carbon emissions in all stages of the supply chain. Therefore, the impact of ethanol demand on supply chain optimization is analyzed by setting the ethanol demand to the fluctuation levels of −20%, −10%, or +10% (when the ethanol demand is set to increase by 20%, the model have no solution due to insufficient raw material production, so, this level is not used). The results of the dual-objective supply chain optimization model at different ethanol demand levels are shown in Figure 4D. From the figure, it can be seen that the total cost at the three levels of ethanol demand fluctuates with the same trend as carbon emissions: decreasing as it increased, but having slightly different reduction rates. When the ethanol demand decreases by 20% and increases by 10%, the rate of cost reduction first accelerates, then slows down, and then accelerates again, However, when the ethanol demand decreases by 10%, the rate of cost reduction won't change significantly.

In conclusion, when the ethanol demand decreases (−10% and −20%), the economic and environmental objectives are better than those in the base scenario and, when the raw material production increases (+10%), the economic and environmental objectives of the model are higher than those in the base scenario (Table S3). This indicates that, when the ethanol demand decreases, the total cost and carbon emissions of the entire supply chain decrease, while the total cost and carbon emissions increase when the ethanol demand increases. This is attributed to the raw materials become sufficient when the ethanol demand decreases, allowing more ample space for the selection of various facility sites. In terms of the number of facilities and transportation routes, with an increase in ethanol demand, the number of raw material collection station increases, and the transportation routes from raw material collection station to ethanol processing plants also increase, indicating that the location of raw material collection station tends to become dispersed as ethanol demand increases. This is opposite to the scenario when raw material production increases, as the raw material production is limited, requiring a greater number of raw material collection station to meet the ethanol demand.

CONCLUSION

This study combines fine-grained growth process model simulation, GIS spatial analysis methods and the integrated optimization capability of the supply chain optimization model to solve the key problems in the development of the sweet sorghum ethanol supply chain industry in China, such as where to get the raw materials from, how to lay out the ethanol processing plant, and how to allocate the raw materials and ethanol products. The main conclusions are as follows:

(1) The sweet sorghum production potential and energy potential of marginal land in China are estimated. The area of marginal land suitable for growing sweet sorghum in China is about 339,000 square kilometers, and the total aboveground biomass (dry weight) of sweet sorghum on marginal land is about 595.39 million tons, which can be converted into a total fuel ethanol production of about 37.212 million tons. It is estimated that China's 2020 demand for automotive fuel ethanol will be about 13 million tons. Therefore, the sweet sorghum production of marginal land can meet the feedstock supply demand for fuel ethanol needed to promote 10% substitution rate automotive ethanol gasoline nationwide.

(2) An optimization scheme for the sweet sorghum ethanol supply chain in China is proposed using economic and ecological benefits as constraints. Utilizing the precise simulation-derived sweet sorghum yields from marginal land as the raw material and the demand for fuel ethanol as the target, the annual lowest cost of the sweet sorghum ethanol supply chain based on the road transportation network is 211.253 billion yuan, with an annual lowest carbon emission of 88.781 billion kilograms. The lowest cost supply chain layout scheme recommends the establishment of large-scale ethanol processing plants near the Hu Huanyong Line.

This study uses explores the optimization of China's sweet sorghum ethanol supply chain, considering fine spatial scales and actual demand. It advances research in China's fuel ethanol sector and provides key references for developing ethanol supply chains from other biomass feedstocks.

REFERENCES

1. Fan, J.L., Fu, J., Zhang, X., et al. (2023). Co-firing plants with retrofitted carbon capture and storage for power-sector emissions mitigation. Nat. Clim. Change 13: 807–815. DOI: 10.1038/s41558-023-01736-y.
2. Fajardy, M., Morris, J., Gurgel, A., et al. (2021). The economics of bioenergy with carbon capture and storage (BECCS) deployment in a 1.5 ℃ or 2 ℃ world. Glob. Environ. Change 68: 102262. DOI: 10.1016/j.gloenvcha.2021.102262.
3. Zhang, B., Hastings, A., Clifton - Brown, J.C., et al. (2020). Modeled spatial assessment of biomass productivity and technical potential of *Miscanthus × giganteus, Panicum virgatum* L. , and Jatropha on marginal land in China. GCB Bioenergy 12: 328–345. DOI: 10.1111/gcbb.12673.
4. Soleimani, H., Govindan, K., Saghafi, H., et al. (2017). Fuzzy multi-objective sustainable and green closed-loop supply chain network design. Comput. Ind. Eng. 109: 191–203. DOI: 10.1016/j.cie.2017.04.038.
5. Jayarathna, L., Kent, G., O'Hara I, et al. (2020). A Geographical Information System based framework to identify optimal location and size of biomass energy plants using single or multiple biomass types. Appl. Energy 275: 115398. DOI: 10.1016/j.apenergy.2020.115398.
6. Fang, Y.R., Shi, W., and Xie, G.H. (2022). Implications of wheat straw logistic systems for bioenergy sustainable development in China: Costs, energy consumption, and GHG emissions. Sci. Total Environ. 837: 155633. DOI: 10.1016/j.scitotenv.2022.155633.
7. Rabbani, M., Saravi, N.A., Farrokhi-Asl, H., et al. (2018). Developing a sustainable supply chain optimization model for switchgrass-based bioenergy production: A case study. J. Clean. Prod. 200: 827–843. DOI: 10.1016/j.jclepro.2018.07.226.
8. Mamoudan, M.M., Jafari, A., Mohammadnazari, Z., et al. (2023). Hybrid machine learning-metaheuristic model for sustainable agri-food production and supply chain planning under water scarcity. Resour. Environ. Sustain. 14: 100133. DOI: 10.1016/j.resenv.2023.100133.
9. Valderrama, C.V., Santibanez-González, E., Pimentel, B., et al. (2020). Designing an environmental supply chain network in the mining industry to reduce carbon emissions. J. Clean. Prod. 254: 119688. DOI: 10.1016/j.jclepro.2019.119688.
10. Zhang, S., Liu, L., Zhang, L., et al. (2018). An optimization model for carbon capture utilization and storage supply chain: A case study in Northeastern China. Appl. Energy 231: 194–206. DOI: 10.1016/j.apenergy.2018.09.129.
11. Lin, T., Rodríguez, L.F., Shastri, Y.N., et al. (2014). Integrated strategic and tactical biomass–biofuel supply chain optimization. Bioresour. technol. 156: 256–266. DOI: 10.1016/j.biortech.2013.12.121.
12. Sharma, B., Ingalls, R.G., Jones, C.L., et al. (2013). Biomass supply chain design and analysis: Basis, overview, modeling, challenges, and future. Renew. Sust. Energ. Rev. 24: 608–627. DOI: 10.1016/j.rser.2013.03.049.
13. Marvin, W.A., Schmidt, L.D., Benjaafar, S., et al. (2011). Optimizing the lignocellulosic

biomass-to-ethanol supply chain: A case study for the Midwestern United States. Comput. Aided Chem. Eng. 29: 1728–1732. DOI: 10.1016/B978-0-444-54298-4.50124-0.
14. Durmaz, Y.G. and Bilgen, B. (2020). Multi-objective optimization of sustainable biomass supply chain network design. Appl. Energy 272: 115259. DOI: 10.1016/j.apenergy.2020.115259.
15. Goli, A., Ala, A., and Mirjalili, S. (2023a). A robust possibilistic programming framework for designing an organ transplant supply chain under uncertainty. Ann. Oper. Res. 328: 493–530. DOI: 10.1007/s10479-022-04829-7.
16. Goli, A., Ala, A., and Hajiaghaei-Keshteli, M. (2023b). Efficient multi-objective meta-heuristic algorithms for energy-aware non-permutation flow-shop scheduling problem. Expert Syst. Appl. 213: 119077. DOI: 10.1016/j.eswa.2022.119077.
17. Goli, A. and Tirkolaee, E.B. (2023c). Designing a portfolio-based closed-loop supply chain network for dairy products with a financial approach: Accelerated Benders decomposition algorithm. Comput. Oper. Res. 155: 106244. DOI: 10.1016/j.cor.2023.106244.
18. Goli, A. (2023d). Integration of blockchain-enabled closed-loop supply chain and robust product portfolio design. Comput. Ind. Eng. 179: 109211. DOI: 10.1016/j.cie.2023.109211.
19. Kostin, A., Macowski, D.H., Pietrobelli, J.M.T.A., et al. (2018). Optimization-based approach for maximizing profitability of bioethanol supply chain in Brazil. Comput. Chem. Eng. 115: 121–132. DOI: 10.1016/j.compchemeng.2018.04.001.
20. Huang, E., Zhang, X., Rodriguez, L., et al. (2019). Multi-objective optimization for sustainable renewable jet fuel production: A case study of corn stover based supply chain system in Midwestern U. S. Renew. Sust. Energ. Rev. 115: 109403. DOI: 10.1016/j.rser.2019.109403.
21. Galanopoulos, C., Giuliano, A., Barletta, D., et al. (2020). An integrated methodology for the economic and environmental assessment of a biorefinery supply chain. Chem. Eng. Res. Des. 160: 199–215. DOI: 10.1016/j.cherd.2020.05.016.
22. Ahranjani, P.M., Ghaderi, S.F., Azadeh, A., et al. (2020). Robust design of a sustainable and resilient bioethanol supply chain under operational and disruption risks. Clean Techn. Environ. Policy 22: 119–151. DOI: 10.1007/s10098-019-01773-2.
23. Akbarian-Saravi, N., Mobini, M., and Rabbani, M. (2020). Development of a comprehensive decision support tool for strategic and tactical planning of a sustainable bioethanol supply chain: Real case study, discussions and policy implications. J. Clean. Prod. 244: 118871. DOI: 10.1016/j.jclepro.2019.118871.
24. Jiang, D., Hao, M., Fu, J., et al. (2019). Potential bioethanol production from sweet sorghum on marginal land in China. J. Clean. Prod. 220: 225–234. DOI: 10.1016/j.jclepro.2019.01.294.
25. Fu, J., Yan, X., and Jiang, D. (2021). Assessing the sweet sorghum-based ethanol potential on saline–alkali land with DSSAT model and LCA approach. Biotech. Biofuel. 14: 1–14. DOI: 10.1186/s13068-021-01896-z.
26. Kong, J., Luo, Y., and Hu, A. (2023). Review of China's refined oil market in 2022 and forecast of supply and demand in 2023. Int. Petrol. Eco. 31: 59–66.
27. Saltelli, A., Tarantola, S., Campolongo, F., et al. (2004). Sensitivity analysis in practice: A guide to assessing scientific models (Halsted Press, USA).
28. Blasone, R.S., Vrugt, J.A., Madsen, H., et al. (2008). Generalized likelihood uncertainty estimation (GLUE) using adaptive Markov Chain Monte Carlo sampling. Adv. Water Resour. 31: 630–648. DOI: 10.1016/j.advwatres.2007.12.003.
29. Wang, Z., Yue, Q., Xia, H., et al. (2016). China 2050: Climate scenarios and stability of Hu-line. Sci. Sin. Terrae 46: 1505–1514. DOI: 10.1360/N072015-00527.
30. Liu, Z., Qiu, T., and Chen, B. (2014). A study of the LCA based biofuel supply chain multi-objective optimization model with multi-conversion paths in China. Appl. Energy 126: 221–234. DOI: 10.1016/j.apenergy.2014.04.001.
31. Tian, Y.S., Li, S.Z., Zhao, L.X., et al. (2011). Life cycle assessment on fuel ethanol producing from sweet sorghum stalks. Tran. Chin. Soc. Agri. Machin. 42: 132–137.
32. Wang, J.Y., Fu, J.Y., Zhao, Z.T., et al. (2023). Benefit analysis of multi-approach biomass energy utilization toward carbon neutrality. The Innovation 4: 100423. DOI: 10.1016/j.xinn.2023.100423.
33. Yin, Z.C., Zhou, B.T., Duan, M.K., et al. Climate extremes become increasingly fierce in China. The Innovation 4: 100406. DOI: 10.1016/j.xinn.2023.100406.

FUNDING AND ACKNOWLEDGMENTS

This study was financially supported by the National Nature Science Foundation of China (No. 42202280). The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

D.J. and J.F. initiated this study and led the writing of the manuscript. T.P., Z.B, G.L. and Q.Z. performed the data processing and analysis. All authors participated in the discussion and writing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

It can be found online at https://doi.org/10.59717/j.xinn-energy.2024.100038

LEAD CONTACT WEBSITE

http://english.igsnrr.cas.cn/about/leadership/202401/t20240131_656860.html