A Comprehensive Evaluation and Optimal Utilization Structure of Crop Straw-based Energy Production in Eastern China

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Crop straw is a major agricultural residue and has been recently promoted as a main source for renewable biomass energy production in China. This study used the fuzzy analytical hierarchy process (Fuzzy AHP) model considering four major indicators to systematically evaluate the performance of four major crop straw energy utilization methods in the eastern Chinese province of Jiangsu. The utilization methods include straw power generation, straw gasification, straw liquefaction, and straw densification into briquette fuel. The results showed that environmental friendliness was the most important indicator that should be considered for straw bioenergy production in the province and that straw densification into briquette fuel was the most suitable straw energy utilization method. Under the policy goal proposed by the Chinese central government to use 20% of all crop straw waste for straw bioenergy production by 2030, the estimated results suggested that the optimal allocation towards straw energy production structure is 40.1% for straw densification into briquette fuel production, 35.3% for straw power generation, 19.6% for straw gasification, and 5% for straw liquefaction. The finding that straw densification into briquette fuel was judged to be the most favorable option could guide policy makers and investors to develop suitable straw energy technologies in Eastern China.

Keywords: Crop straw; Bioenergy; Fuzzy-AHP; Comprehensive evaluation; Structure optimization

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INTRODUCTION

Energy is a key source for economic development in many countries around the world. Fossil fuel-based energy is non-renewable and is facing the threat of exhaustion (Parikka 2004). Biomass energy is an emerging alternative to traditional fossil fuels due to its environmental friendliness and renewability (Hillring and Trossero 2006; Wang *et al*. 2018a; Fang *et al.* 2019). In China, crop straw (*e.g.*, rice, corn, and wheat) is a major agricultural waste and has traditionally been the major fuel source for households in rural areas. The annual crop straw waste in China is approximately 300 million tons (Zhang *et al*. 2004). However, the traditional straw waste usage by simple combustion techniques (*e.g.*, either used for household cooking, heating, or direct burning in crop fields) often results in a low burning efficiency and high carbon emissions that contribute to severe haze pollution in China. Thus, other environmentally friendly and value-added biofuel forms have been promoted and developed recently in China *via* various straw conversion methods (Wang *et al*. 2018b; Song *et al*. 2019; Zhang *et al*. 2019). Specifically, in May 2015, the Chinese central government issued the "National Plan for Sustainable Agricultural

Development (2015-2030)" (The Ministry of Agriculture of the People's Republic of China 2015), which aims to achieve the full utilization of straw waste by 2030. By the end of 2017, the utilization rate of straw waste in China reached 83.7%, 15.2% of which was utilized for renewable bioenergy production. The government targets 20% of straw waste in China to be used for bioenergy production by 2030. Thus, effectively using crop straw bioresources and developing straw-related bioenergies and industries could not only alleviate the reliance on traditional fossil fuels and improve rural environments but also create new jobs and meet the goal of green economic development in rural areas.

There are four main methods of straw energy utilization that are being developed in China and many other countries. These methods include: (1) direct straw combustion for power generation (hereafter called straw power generation), (2) straw gasification, (3) straw liquefaction (*i.e.*, bioethanol), and (4) straw densification into briquette fuel (Dong *et al*. 2010). Straw power generation is a mature energy conversion method. At present, the key equipment and facilities are highly localized, with a high industrialization level. The major hurdles facing straw power generation include storing and transporting raw materials and the supply shortage, which seriously affects the economic feasibility of straw power generation projects in China and other countries (Singh 2016; Shi *et al*. 2018). Straw gasification has become a widely used method in agricultural practice in recent years, and the industry has developed rapidly (Zeng *et al*. 2007; Chen *et al*. 2010a; Zhu *et al.* 2017). However, there are several problems, such as a low gas production rate, difficulty in feeding and discharging raw materials, tar treatments, and secondary pollution, which have resulted in few projects achieving stable operation (FAO 2009; Chen *et al*. 2010a). Straw liquefaction (*e.g.*, cellulosic ethanol) products have high economic benefits and are being promoted in China and other regions of world, such as Europe, the United States, and Brazil (European Technology and Innovation Platform Bioenergy 2019). In China, the central government has invested significant funds to support the research and development of the straw liquefaction industry. However, high capital costs are among the major challenges that the industry is facing in the development of straw liquefaction technology (Zhu *et al*. 2017; Ren *et al*. 2019). Finally, straw densification into briquette fuel (including pellets) has been consistently developed in China, with a complete supply chain and mature technology for fuel production. Large dimension, block-shaped, straw briquettes are more common in China than small size straw pellets. Straw densification into briquette fuel yields a solid fuel with the advantages of a small size, convenience for long-distance transport, and easy long-term storage. Moreover, the straw-based briquette fuel is considered a clean energy with low carbon emissions, little ash, and a high fuel burning efficiency (Chen *et al*. 2010b). Thus, burning this fuel can improve the rural environment compared with the direct combustion of straw waste. The straw solid fuel can also be transformed from small-scale household usage to large-scale industrial applications, and this technology has been widely promoted by the government for large-scale industrial and commercial operations that use crop straw resources in China (Ruan *et al*. 2014).

The feasibility analysis of straw utilization and related bioenergy development in China has been investigated by previous researchers. Ren *et al*. (2019) reviewed the status of relevant laws, regulations, policies, and management practices of crop straw utilization in China. The cited study also found that there is a lack of adequate government financial support and a lack of infrastructure and logistics to support the complex operation of straw collection, transportation, storage, *etc.*, which are the main obstacles for straw utilization in China. Thus, to efficiently use crop straw as bioresources and reduce open-field straw burning, the authors suggested that the government should shift from the current administrative, prohibition, and penalty-based policies to polices that are long-term, cohesive, and economically effective straw utilization policies. Wang *et al*. (2018b) examined the current status of straw energy production in the Jilin Province and estimated the future (2015 through 2030) potential for straw supply and socioeconomic and environmental benefits associated with the development of three straw bioenergy utilization methods, including straw power generation, straw liquefaction (*e.g.*, cellulosic fuel ethanol), and straw densification into briquette fuel in the province. The authors found that developing bioenergy industries could generate a significant amount of environmental and socioeconomic benefits in the province. Dong *et al*. (2010) compared the straw bioenergy utilization methods from four aspects (*i.e.*, rationale, operating conditions, equipment, and economic efficiency) and found that the utilization rate and economic efficiency of straw liquefaction to ethanol were higher than those of other four straw energy utilization methods. Moreover, Li *et al*. (2012) simulated the industrial structures of straw power generation, straw liquefaction, and papermaking and found that straw used for power generation accounted for a large proportion of the utilization structure in all four scenarios. Straw collection technology and bioethanol subsidies were the key factors that affected industrial development. Most of these studies on the evaluation of straw energy utilization have been qualitative in nature and tended to evaluate the advantages and disadvantages of various straw energy utilization methods. Few researchers have used quantitative and systematic analysis methods to investigate the optimal straw energy utilization approach in China. In one of few such studies, Li *et al*. (2016) conducted a life cycle analysis to evaluate straw power generation and straw liquefaction for bio-ethanol. The cited authors found that both of these straw bioenergy utilization methods could significantly reduce greenhouse gas emissions, despite not being sustainable. Based on the literature review, the authors found few studies that investigated optimal straw energy production in China using quantitative approaches. Moreover, in the selection of performance evaluation indicators for different straw energy utilization methods, previous studies have focused on indicators, such as resource availability, technical feasibility, and economic benefits, and paid less attention to the indicators related to social and environmental factors.

The analytical hierarchy process (AHP) has been widely used to aid the decision-making process related to energy planning and usage (Nigim *et al*. 2004; Pohekar and Ramachandran 2004; Li *et al*. 2011). To overcome personal subjective judgment, uncertainty, and selection preference problems in AHP, which may bias the results, the authors developed an evaluation framework that considers technical, social, economic, and environmental indicators for the major straw energy production methods in the eastern Chinese province of Jiangsu using the Fuzzy AHP method (Laarhoven and Pedrycz 1983; Shapiro and Koissi 2017). The explored straw energy utilization methods include straw power generation, straw gasification, straw liquefaction, and straw densification into briquette fuel. The major research questions that were studied were (1) which straw energy utilization method is most suitable/preferred and should be prioritized by the government for further development in Jiangsu Province and (2) what is the most desirable structure allocation for the major straw energy production methods in the province? A linear programming method was used to investigate the optimal industrial structure allocation for the four main straw bioenergy production methods in the province in 2030 considering the proposed policy goals and related social, economic, and environmental constraints. To the best of the authors' knowledge, this is the first attempt to comprehensively study the optimal straw energy utilization structure in China using the Fuzzy AHP method. Using

Jiangsu Province as a case study, the results of this research not only provide guidance for decision makers regarding straw energy utilization and industrial development but also provide insight into energy utilization in resource-scarce regions/provinces.

EXPERIMENTAL

Materials and Methods

Located in the eastern coastal region of mainland China, Jiangsu province is one of the most important areas producing grains, such as rice, wheat, corn, and rapeseed, and has abundant crop straw resources. According to the provincial government report, "Guidelines for the Implementation of Comprehensive Utilization of Crop Straw in Jiangsu Province in 2017" (Jiangsu Provincial People's Government 2017), the annual crop straw supply in Jiangsu province was approximately 40 million tons, and more than 80% of the supply was composed of wheat and rice, which provides ample supply for straw-related bioenergy utilization. In contrast, as a highly developed province in China (the 2nd richest province in China, next to the Guangdong province), the Jiangsu province faces the highest energy demand. Thus, to solve the potential energy crisis, Jiangsu is one of the pilot provinces under the Renewable Energy Law and the only province in China to fully develop biomass energy for its major energy sources. In 2017, there were approximately 600 straw bioenergy companies in the province, and the total amount of straw waste used for bioenergy production was approximately 5 million tons in the province (equal to 12.5% usage rate) (Jiangsu Provincial People's Government 2015).

To evaluate straw energy utilization in China, this study constructed a comprehensive performance evaluation framework for various straw energy production methods and investigated the optimal utilization structure for different straw energy technologies (see Fig. 1)..

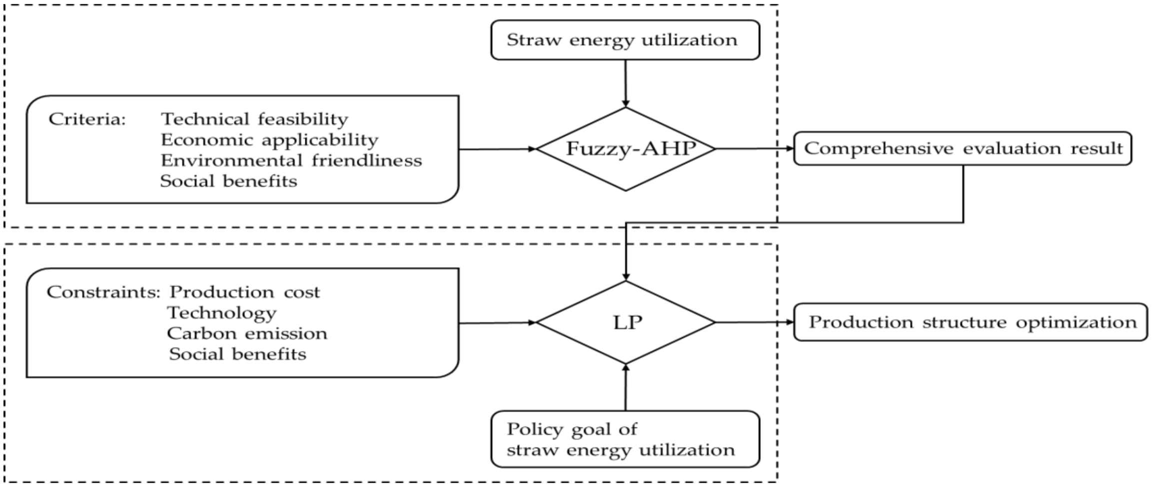

Fig. 1. Straw energy utilization evaluation framework and structure optimization model; Fuzzy AHP = fuzzy analytical hierarchy process; LP = linear programming

Specifically, the analysis included two parts. First, the Fuzzy AHP method was used to evaluate and rank the four straw energy utilization methods based on four main indicators. The indicators used included technical feasibility, economic applicability, environmental friendliness, and social benefits. Second, the results from the first part were further used to investigate the optimal straw energy utilization structure using a linear programming method considering various constraints, such as the related costs, applicable technology, carbon emission level, and social benefits.

Following the evaluation framework for renewable energy utilization in China by Li *et al*. (2011), an evaluation framework was constructed for straw energy utilization with four major indicators (including technical feasibility, economic applicability, environmental friendliness, and social benefits) and eleven sub-indicators for Jiangsu province (see Table 1). The selection criteria and data used for evaluating these indicators were based on previous studies and expert opinions, as well as considerations of data availability, indicator plausibility, and the suitability of current straw energy utilization and development in the province.

Table 1. Evaluation Indicators, Types, and Data Sources

Major Indicators (Code)	Sub-indicators (Code)	Type	Data Source
Technical feasibility (A)	Energy conversion rate (A_1)	Quantitative	Tian *et al*. (2011a); Wang *et al*. (2012); Dong and Liu (2013); Fu and Wu (2014)
	Technological maturity (A_2)	Qualitative	Expert survey (1 to 9 scale)
	Resource supply (A_3)	Quantitative	Wang *et al*. (2010)
Economic applicability (B)	Energy grade (B_1)	Qualitative	Expert survey (1 to 9 scale)
	Production cost (B_2)	Quantitative	Song *et al*. (2010); Tian *et al*. (2011a); Wang *et al*. (2012); Dong and Liu (2013)
	Price ratio to substituted products (B_3)	Quantitative	Dong *et al*. (2010); Wang *et al*. (2012); Dong and Liu (2013)
Environmental friendliness (C)	CO_2 emission reduction (C_1)	Quantitative	Song *et al*. (2010); Tian *et al*. (2011a); Wang *et al*. (2012); Dong and Liu (2013)
	Generation of other pollutants (C_2)	Qualitative	Expert survey (1 to 9 scale)
	Circular benefit (C_3)	Qualitative	Expert survey (1 to 9 scale)
Social effectiveness (D)	Job creation (D_1)	Quantitative	Dong *et al*. (2010); Wang *et al*. (2012); Li *et al*. (2016); Wang *et al*. (2018b)
	Increase in farmers' income (D_2)	Quantitative	Dong *et al*. (2010); Wang *et al*. (2012); Li *et al*. (2016) Wang *et al*. (2018b)

Technical feasibility indicators

Technical feasibility is an indicator used to evaluate the efficiency and feasibility of straw energy utilization. There were three sub-indicators used in the analysis: energy conversion rate, technological maturity, and the resource supply.

1. *Energy conversion rate*: As a quantitative indicator, the energy conversion rate refers to the technical application efficiency of different straw energy utilization methods. Various straw energy utilization methods use different equipment and technical inputs.

A high energy conversion rate reflects a high utilization rate of raw materials. The energy conversion rate was expressed as follows:

$$\beta\ (\%) = \frac{M_1}{M_0} \times 100 \tag{1}$$

where β is the energy conversion rate and M_0 and M_1 are the input and output of energy processing and transformation, respectively.

2. *Technological maturity*: As a qualitative indicator, this measures the technological level of different straw energy utilization methods. The technical level affects the efficiency and development of straw energy conversion. Following the definition of the technological maturity level (TML) of the U. S. Department of Defense (Wang 2009), the authors divided the technological maturity of straw energy utilization into nine levels ranging from very poor to very good, and data were collected from an expert survey.
3. *Resource supply*: As a quantitative indicator, the resource supply ensures the sustainability of energy conversion. The crop straw wastes in China are mainly from corn, rice, and wheat. The straw supply quantity considered in this study was the theoretical supply, which was calculated according to the average crop yield and ratios of grain and straw in China. Additionally, the data for the straw supply quantity for each straw energy utilization methods were collected from an expert survey (Tian *et al*. 2011b).

Economic applicability indicators

Economic applicability is used to evaluate the economic efficiency and cost effectiveness of straw energy utilization. There are three sub-indicators considered in this study: the energy grade, production cost, and price ratio for substituted products.

1. *Energy grade*: As a qualitative indicator, the energy grade data were collected from the expert survey, where respondents were asked to grade the bioenergy generated from various straw energy technologies on a scale from very poor to very good (1 to 9). The authors assumed that this indicator was also a proxy for the market demand of various straw bioenergies (Wang *et al*. 2012).
2. *Production cost*: As a quantitative indicator, the production cost considered in this paper includes the raw material cost, construction cost, and operation cost for each straw energy utilization method. The straw energy utilization methods were assumed to have the following production capacities in this study for cost estimation: (1) a straw power generation project was investigated with an installed capacity of 25 WM per year, (2) a straw ethanol project was investigated with a production capacity of 300 tons per year, (3) a straw gasification and centralized gas supply project was investigated with a gas supply capacity of 300 households per year, and (4) a straw densification to briquette fuel was investigated with an annual output of 20,000 tons (Tian *et al*. 2011a; Wang *et al*. 2012; Dong and Liu 2013). To compare various methods, the production cost for each energy utilization method was converted into the unit production cost required to produce one ton of coal equivalent (TCE) for comparison.
3. *Price ratio for substituted products*: As a quantitative indicator, the price ratio for substituted products reflects whether straw-based alternative energy products have

comparative advantages over traditional fossil fuels. For example, a lower price ratio of a selected straw-based energy product to a substituted traditional fossil fuel product results in higher incentives for consumers to adopt the new straw bioenergy product.

Environmental friendliness indicators

Straw-based energy products are characterized by a high burning efficiency, little ash, and a low sulfur content, and the corresponding production methods are considered to be more environmentally friendly than traditional direct combustion methods. There were three sub-indicators considered: CO_2 emission reduction, the generation of other pollutants, and circular benefits.

1. *CO_2 emission reduction*: As a quantitative indicator, the CO_2 emission reduction calculated in this study was based on how many TCE could be saved under various straw energy utilization methods. Specifically, how much energy (in units of TCE) could be generated from per ton of straw waste input from each energy utilization method was calculated first. Then, a transfer coefficient of 2.814 tons of CO_2 emissions per TCE of energy production was used to calculate the CO_2 emission reductions for different straw energy utilization methods (Hou *et al*. 2015; Mou *et al*. 2017).
2. *Generation of other pollutants*: As a qualitative indicator, this evaluates the related wastes and pollutants (*i.e.*, sulfide, nitride, wastewater, or waste residue) generated from different straw energy utilization methods for comparison. Data were collected from an expert survey based on a scale of 1 to 9.
3. *Circular benefits*: As a qualitative indicator, this indicator reflects clean production and was evaluated from an expert survey based on the straw waste usage, emission level, and energy production efficiency during the energy production process of each straw energy utilization method.

Social benefit indicators

Because straw waste is a major agricultural residue, the development of straw energy technology may affect the livelihoods of residents in rural areas. Two sub-indicators were considered in this study: job creation and increased farmers' income.

1. *Job creation*: As a quantitative indicator based on previous studies (Dong *et al*. 2010; Wang *et al*. 2012; Li *et al*. 2016; Wang *et al*. 2018b;), it was assumed that one job will be created based on the following straw energy production capacities: (1) per 40,000 kWh of energy production from straw power generation, (2) per cubic meter of energy production from straw gasification, (3) per 200 tons of energy production from straw liquefaction, and (4) per 500 tons of solid fuel production from straw densification into briquette fuel.
2. *Increase farmers' income*: As a quantitative indicator similar to the job creation as mentioned above. With the support from the provincial and local governments to develop straw-based energy industry in Jiangsu, the production capacity for different straw energy utilization methods and demand for crop straw feedstock will continue to grow over time. Thus, the assumed income increases from the sale of straw for different straw energy utilization methods were (1) CNY \$0.17/kWh for straw power generation, (2) CNY \$1.02/m^3 for straw gasification, (3) CNY \$3100/ton for straw liquefaction, and (4) CNY \$150/ton for straw densification into briquette fuel.

Indicator Data Processing

The 11 sub-indicators included quantitative and qualitative indicators. The data used for the quantitative indicators were based on the authors' estimations, whereas the data for qualitative indicators were from an expert survey that the authors conducted in April 2016. The selection criteria for the respondents who took the expert survey were based on Citespace, which is a citation visualization analysis software package (Citespace, version 4.4, Drexel University, Philadelphia, PA, USA). Specifically, the study of straw energy utilization in China as the research object. Citespace generated an institutional contribution map and author contribution map for the highly cited scholars in this area. Four experts in the field of straw energy utilization were identified and invited to take the survey to assess the qualitative indicators for each straw energy utilization method and to accomplish a pairwise comparison of the relative importance of all major indicators and sub-indicators. The four selected experts are affiliated with Beijing Forestry University in Beijing, Northeast Forestry University in Heilongjiang Province, the Institute of Chemical Industry of Forest Products, Chinese Academy of Forestry in Jiangsu Province, and the Academy of Forestry in Hubei Province.

The efficacy coefficient method was adopted for the data standardization of each indicator under various straw energy utilization methods, which reflected the relative importance of a specific energy utilization method compared to the other three straw energy utilization methods under the same indicator (Li *et al*. 2011). For example, for the benefit-related indicators (*e.g.*, indicators A_1, A_2, A_3, B_1, C_1, C_3, D_1, and D_2), the following formula (Eq. 2) was adopted for standardization:

$$U(X_i) = \frac{X_\mathrm{i} - X_\mathrm{min}}{X_\mathrm{max} - X_\mathrm{min}} \times 40 + 60 \tag{2}$$

For the cost-related indicators (*e.g.*, indicators B_2, B_3, and C_2), the following formula (Eq. 3) was adopted for standardization,

$$U(X_\mathrm{i}) = \frac{X_\mathrm{max} - X_\mathrm{i}}{X_\mathrm{max} - X_\mathrm{min}} \times 40 + 60 \tag{3}$$

where $\mathrm{U}(X_\mathrm{i})$ represents the standardized data of indicator *i*, X_i represents the original data value of indicator *i* of the investigated energy utilization method, X_max is the maximum value of indicator *i* among the four straw energy utilization methods in the dataset, and X_min is the minimum value of indicator *i* among the four energy utilization methods in the dataset.

Fuzzy AHP Method

Following Laarhoven and Pedrycz's (1983) criteria and the steps for implementing the Fuzzy AHP method, first the AHP hierarchy as shown in Fig. 2 was established based on the overall decision-making objectives, AHP stratification principle, and alternatives.

Second, the four selected experts were asked to evaluate the relative importance of indicators based on a pairwise comparison considering the major criterion and sub-criterion layers using the AHP relative intensity scale from extremely important to extremely unimportant (1 to 9) (see Table 2 for the relative intensity definitions). A corresponding triangular fuzzy number was further constructed based on the relative intensity scale. The triangular fuzzy judgment matrix was presented as $\mathrm{A} = (a_\mathrm{ij})_\mathrm{n\times n}$, in which the element $a_\mathrm{ij}(u_\mathrm{ij}, m_\mathrm{ij}, l_\mathrm{ij})$ is a closed interval with u_ij as the upper bound, m_ij as the median, and l_ij as the lower bound.

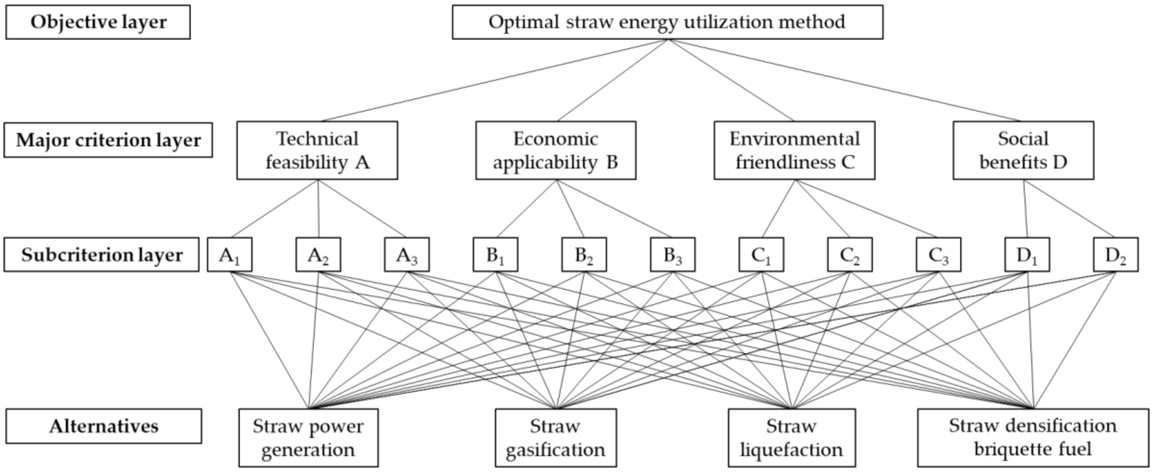

Fig. 2. Hierarchical structure of straw energy utilization

Table 2. Intensity Scale for Criteria Pairwise Comparison and Triangular Fuzzy Values

Intensity Scale (From 1 to 9)	Importance Definition	Triangular Fuzzy Values
1	X_i is extremely more important than X_j	(0.8, 0.9, 1)
2	X_i is very strongly more important than X_j	(0.7, 0.8.0.9)
3	X_i is strongly more important than X_j	(0.6, 0.7, 0.8)
4	X_i is moderately more important than X_j	(0.5, 0.6, 0.7)
5	X_i is equally important with X_j	(0.5, 0.5, 0.5)
6	X_i is moderately less important than X_j	(0.3, 0.4, 0.5)
7	X_i is strongly less important than X_j	(0.2, 0.3, 0.4)
8	X_i is very strongly less important than X_j	(0.1, 0.2, 0.3)
9	X_i is extremely less important than X_j	(0, 0.1, 0.2)

Note: *X*i and *X*j are indicators of the major criteria or sub-criteria layers for pairwise comparison in the expert survey

Third, the comprehensive importance value was calculated. The comprehensive degree of each element in the kth layer (*i.e.*, major criterion or sub-criterion) with all other elements can be expressed by S_i^k:

$$S_i^k = \sum_{j=1}^{n} a_{ij}^k \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij}^k\right], i = 1,2,\cdots\cdots,n \tag{4}$$

Finally, the hierarchical weights and total weights were calculated. The evaluation indicators were processed by the efficacy coefficient method discussed above, and the comprehensive performance evaluation values were calculated and used to rank the different straw energy utilization methods.

Structure Optimization for Straw Energy Utilization

Although Fuzzy AHP yields a comprehensive evaluation result based on a series of core indicators for the weights, rankings, or preferences of different straw energy utilization methods, it does not consider several practical constraints when policymakers develop straw energy utilization technologies. Thus, based on the evaluation results from

Fuzzy AHP, the authors further investigated the optimal structure allocation for various straw energy technologies using a linear programming model. Specifically, the authors first maximized the comprehensive performance evaluation values of many straw energy utilization combinations as the objective function subject to various technical, economic, social, and environmental constraints considered by decision makers, which can be expressed as follows (Eq. 5),

$$max\, z = \sum_{i=1}^{4} X_i n_i \tag{5}$$

Subject to

$$\begin{cases} \sum_{i=1}^{4} n_i = 1 \\ \sum_{i=1}^{4} C_i \leq \sum_{i=1}^{4} C_i^* \\ \sum_{i=1}^{4} T_i \geq \sum_{i=1}^{4} T_i^* \\ \sum_{i=1}^{4} CO_{2i} \leq \sum_{i=1}^{4} CO_{2i}^* \\ \sum_{i=1}^{4} E_i \geq \sum_{i=1}^{4} E_i^* \\ \sum_{i=1}^{4} I_i \geq \sum_{i=1}^{4} I_i^* \\ n_i \geq 5\% \end{cases} \tag{6}$$

where Eq. 5 is the objective function that maximizes the comprehensive evaluation value z, X_i is the comprehensive evaluation value of a specific straw energy utilization method, n_i is the optimal proportion of a specific straw energy utilization method C_i, T_i, CO_{2i}, E_i, and I_i are the future values of the cost, technological maturity, CO_2 emissions, job creation, and income increase for farmers for different straw energy utilization methods in 2030, respectively, and $C_i^*, T_i^*, CO2_i^*, E_i^*$, and I_i^* are the present values (in 2017) of these variables. The MATLAB software (MATLAB, 2020) with the command "linprog" was used to solve the optimization problem in this study.

In Eq. 6, the specific constraint conditions are explained as follows:

1. The sum of the weights of various straw energy utilization methods is equal to 1.
2. Production cost constraint: The total optimized average straw energy production cost from different straw energy production methods in 2030 should be less than or equal to the total existing cost.
3. Technical constraint: The total optimized average straw energy technical maturity level in 2030 from different straw energy utilization methods should be higher than or equal to the total existing technology level.
4. Carbon emission constraint: The total optimized CO_2 emissions from various straw energy utilization methods in 2030 should be less than or equal to the existing total CO_2 emissions.
5. Social benefit constraints: The total optimized job and farmers' income increase associated with different straw energy utilization methods in 2030 should be higher than or equal to the existing levels.
6. Based on the objective of the Chinese central government that all types of straw energy utilization methods should be developed comprehensively, it was assumed that the optimized structure allocation for each straw energy utilization method should not be less than 5%.

Finally, under the policy goal of using 20% of all crop straw waste for straw energy production in 2030 in China, the optimal structure allocation for the four main straw energy utilization methods in Jiangsu province was simulated in this study. The data for relevant indicators in 2030 used in the simulations were as follows:

1. *Technological maturity*: Technological maturity was based on the expert survey results and data from technical reports published by the Chinese Academy of Sciences and other research reports (Strategic Research Group in Energy Field 2009; Chang *et al*. 2016; Chen *et al*. 2016; Shi *et al*. 2016).
2. *Resource supply*: The authors used the average growth rate of agricultural crop production from the Chinese statistical yearbook to project the potential straw supply in 2030 (Jiang *et al*. 2012; Zhu *et al*. 2016).
3. *Production cost*: The production cost data was obtained from domestic research reports based on the average rate of change of the cost and were used to project the potential production cost of straw energy utilization in 2030 (Chen *et al*. 2016; Zhu *et al*. 2016).
4. *Price ratio for substituted products*: Similar to the production cost, the average rate of change of the price of a specific straw energy over time was used to project the price ratio for substituted products in straw energy utilization in 2030 (Jiang *et al*. 2012; Chang *et al*. 2016).

RESULTS AND DISCUSSION

Comprehensive Evaluation

According to the expert survey results, each expert was given the same weight, and the triangular fuzzy number judgment matrix for the major criterion layer was constructed as follows:

$$A_0 = \begin{bmatrix} (0.500,0.500,0.500) & (0.375,0.475,0.575) & (0.350,0.450,0.550) & (0.450,0.550,0.650) \\ (0.425,0.525,0.625) & (0.500,0.500,0.500) & (0.350,0.450,0.550) & (0.450,0.550,0.650) \\ (0.450,0.550,0.650) & (0.450,0.550,0.650) & (0.500,0.500,0.500) & (0.500,0.600,0.700) \\ (0.350,0.450,0.550) & (0.350,0.450,0.550) & (0.300,0.400,0.500) & (0.500,0.500,0.500) \end{bmatrix}$$

A similar method was used to construct the triangular fuzzy number judgment matrices for the pairwise comparison of the indicators in each sub-criterion layer, and the weights of the 11 sub-criterion indicators were estimated. The results are shown in Table 3. Results in the table show that the weight of environmental friendliness, a major indicator, was 0.295, which ranked first among the four evaluation indicators of the major criterion layer, followed by economic applicability (0.256), technical feasibility (0.252), and social benefits (0.197). These results indicated that environmental friendliness was the most important factor that decision makers should consider when developing the straw energy industry in Jiangsu province. In addition, the weights of indicators did not display large differences, which suggested that these indicators all play important roles in evaluating straw energy utilization in the province.

Table 3. Estimated Weights of Major and Sub-criterion Indicators

Major Indicators	Weight	Sub-criterion Indicators	Weight	Total Weight
Technical feasibility (A)	0.252	Energy conversion rate (A_1)	0.159	0.040
		Technological maturity (A_2)	0.271	0.068
		Resource supply (A_3)	0.570	0.144
Economic applicability (B)	0.256	Energy grade (B_1)	0.274	0.070
		Production cost (B_2)	0.398	0.102
		Price ratio for substituted products (B_3)	0.328	0.084
Environmental friendliness (C)	0.295	CO_2 emission reduction (C_1)	0.300	0.089
		Generation of other wastes (C_2)	0.252	0.074
		Circular benefit (C_3)	0.448	0.132
Social benefits (D)	0.197	Job creation (D_1)	0.571	0.112
		Increase in farmers' income (D_2)	0.429	0.085

Among the 11 sub-indicators, the resource supply had the largest total weight (0.144, see Table 3). Given that the seasonal characteristics, dispersion, and high collection cost of straw waste, determining the appropriate straw collection radius, and collection method is important for straw energy utilization. Taking straw power generation as an example, only one-third of the power plants in China have sufficient straw supplies for power generation due to the hurdles of raw material collection and storage costs, which have forced some straw power plants to stop power generation shortly after operation. Losses caused by insufficient feedstock supplies are a common problem faced by the straw energy industry (Chen *et al*. 2010b).

In addition to the resource supply, several of the total weights of sub-indicators were greater than 0.10, including those for circular benefits (0.132), job creation (0.112), and production costs (0.102). This result implied that these indicators are important factors that decision makers should also consider when developing the straw energy industry in Jiangsu province in the future.

A consistency test of the pairwise comparisons judgment matrices derived from the expert survey was conducted to ensure the validity and reliability of the results (Yang *et al*. 2010). In this study, the threshold of satisfactory consistency for the triangular fuzzy number judgment matrices was set as $\varepsilon = 0.2$. If the calculated consistency value p was less than the threshold value ε, the estimated results were consistent and satisfactory. As shown in Table 4, all the triangular fuzzy number judgment matrices passed the consistency test.

Table 4. Results of the Consistency Test

	ρ_0	ρ_A	ρ_B	ρ_C	ρ_D
ρ Value	0.100	0.025	0.042	0.025	0.000
Result	Passed	Passed	Passed	Passed	Passed

Note: ρ_0 is the consistency value of the major criterion layer, and $\rho_A, \rho_B, \rho_C,$ and ρ_D are the consistency values of the four sub-criterion layers. The threshold value of satisfactory consistency for the triangular fuzzy number judgment matrices was set to $\varepsilon = 0.2$

Comprehensive Evaluation in the Benchmark Year 2017

Table 5 shows the results of data standardization and comprehensive performance evaluation according to Eqs. 2 and 3 in the base year 2017. Results from Table 5 revealed that straw densification into briquette fuel has the highest comprehensive performance evaluation value in base year 2017, followed by straw power generation, straw gasification, and straw liquefaction. Among the four main straw energy production methods that were investigated in this study, the straw densification into briquette fuel was the most preferred utilization technique that should be promoted and developed in Jiangsu province relative to the other straw energy utilization methods. There are several reasons for this preference. First, straw densification into briquette fuel involves simple processing technology, a high-energy conversion rate, good circular benefits, and low costs. Furthermore, the straw-based briquette fuel can be used as an independent energy end-use product, including as a household fuel in rural areas or as heating fuel for district heating. This fuel can also be used as an input for other bioenergy production, such as feedstocks for straw power generation and straw gasification. Thus, under the policies of promoting energy savings and emission reductions in China, developing straw densification into briquette fuel could create a large market demand, expand the feedstock supply chain for other environmentally friendly bioenergy production methods, and increase economic and social benefits when compared with those of other bioenergy utilization methods.

Table 5. Results of Data Standardization and Comprehensive Evaluation in 2017

	Straw Power Generation	Straw Gasification	Straw Liquefaction	Straw Densification into Briquette Fuel
Energy Conversion Rate (A_1)	60.00	86.67	66.67	100.00
Technological Maturity (A_2)	83.53	85.88	60.00	100.00
Resource Supply (A_3)	100.00	65.71	60.00	100.00
Energy Grade (B_1)	90.00	100.00	95.00	60.00
Production Cost (B_2)	89.44	65.98	60.00	100.00
Price Ratio for Substituted Products (B_3)	100.00	60.00	65.71	88.57
CO_2 Emission Reduction (C_1)	85.81	76.77	60.00	100.00
Generation of Other Wastes (C_2)	76.00	100.00	92.00	60.00
Circular Benefit (C_3)	86.67	73.33	60.00	100.00
Job Creation (D_1)	60.00	82.86	65.71	100.00
Increase in Farmers' Income (D_2)	63.33	100.00	80.00	60.00
Comprehensive Evaluation Value	**83.11**	**79.23**	**67.90**	**89.88**
Rank	**2**	**3**	**4**	**1**

Comprehensive Evaluation Analysis in 2030

Table 6 shows the comprehensive assessment scenario results in 2030. Straw densification into briquette fuel will continue to be the most favorable straw energy utilization method that should be promoted in Jiangsu province. Although the ranking of the comprehensive performances of the four straw energy production methods did not change compared with that in the benchmark year 2017, the comprehensive evaluation value of straw gasification showed an increase and approached the value for straw power generation due to the improvement in resource supply and the reduction in production costs. Thus, the advantages of straw gasification will gradually emerge over time. Additionally, straw power generation and straw liquefaction are influenced by the rate of energy conversion, resource supply, and high production cost, which are projected to limit the development of these two straw energy technologies in the near future.

Table 6. Results of Data Standardization and Comprehensive Evaluation in 2030

	Straw Power Generation	Straw Gasification	Straw Liquefaction	Straw Densification into Briquette Fuel
Energy Conversion Rate (A_1)	60.00	87.03	65.41	100.00
Technological Maturity (A_2)	100.00	73.33	60.00	86.67
Resource Supply (A_3)	76.00	80.00	60.00	100.00
Energy Grade (B_1)	90.00	100.00	95.00	60.00
Production Cost (B_2)	98.08	73.90	60.00	100.00
Price Ratio for Substituted Products (B_3)	100.00	60.00	65.71	88.57
CO_2 Emission Reduction (C_1)	85.81	76.77	60.00	100.00
Generation of Other Wastes (C_2)	76.00	100.00	92.00	60.00
Circular Benefit (C_3)	86.67	73.33	60.00	100.00
Job Creation (D_1)	60.00	82.86	65.71	100.00
Increase in Farmers' Income (D_2)	63.33	100.00	80.00	60.00
Comprehensive Evaluation Value	**81.65**	**81.26**	**67.85**	**88.97**
Rank	**2**	**3**	**4**	**1**

Structure Optimization

The results of the comprehensive evaluation in 2030 presented in Table 6 were further used in linear programming to estimate the optimal weights of the four straw energy utilization methods in Jiangsu province in 2030, as shown in Table 7.

Table 7. Optimal Straw Energy Production Structure in Jiangsu Province in 2030

	Straw Power Generation	Straw Gasification	Straw Liquefaction	Straw Densification into Briquette Fuel
Weight	35.34%	19.56%	5.00%	40.10%
Optimal Evaluation Value	83.83			

Based on the "National Plan for Sustainable Agricultural Development (2015-2030)", which indicates that China seeks to fully utilize crop straw wastes by 2030 and reach the goal of using 20% of all crop straw wastes for straw energy production, the authors' results revealed that the straw densification into briquette fuel should continue to be prioritized for development and followed by straw power generation. The straw densification into briquette fuel and straw power generation are the primary bioenergy production methods that are preferred in Jiangsu, and they combine to account for 75% of the optimal energy production structure in the province. However, the straw gasification and straw liquefaction methods should be allocated a relatively small proportion of the overall straw structure in the province. Although the optimal evaluation value (83.83) in Table 7 for the four straw energy utilization methods was lower than the comprehensive evaluation value (88.97, see Table 6) for straw densification into briquette fuel from the Fuzzy AHP method. The results of Table 7 were studied considering the potential cost, technological maturity, carbon emission, and social benefit constraints in 2030 to determine the optimal future development strategy in Jiangsu province for straw bioenergy. The authors believe that the estimated optimal structure allocation for the four straw energy production methods will provide valuable information and closely reflect future straw energy development in the province.

Although this study provides insights for decision makers to develop the straw bioenergy industry in Jiangsu, China, there are several limitations that should be discussed and considered in future research. First, in this study, the authors used only the theoretical straw resource supply, which was based on the crop yields and crop straw ratios, and the authors did not consider the potential straw loss during collection and transportation. Future research should address this issue to obtain better estimations. Additionally, due to data availability and budget limitations, the authors only considered four major indicators and eleven sub-indicators for Jiangsu province. It would be interesting to further expand the hierarchy layers and include more indicators based on the geographic characteristics of a region to provide more accurate and objective evaluations for other Chinese regions or provinces. Finally, the performance of the four straw energy utilization methods was evaluated, and the methods were ranked individually. It is possible that various straw energy utilization methods could be combined. It is the authors' intention to evaluate and compare the performances of hybrid straw energy production methods with individual straw energy technology in the future.

CONCLUSIONS

1. Environmental friendliness (0.295) was accounted for the largest weight among the four major indicators in the criterion layer, followed by economic applicability (0.256) and technical feasibility (0.252), and social benefits (0.197) ranked last. Meanwhile, resource supply has the largest total weight (0.144) among the 11 sub-indicators.
2. Straw densification into briquette fuel is the most preferred straw energy utilization technique that should be promoted and developed in Jiangsu province relative to the other straw energy utilization methods, while the advantages of straw gasification will gradually emerge over time.
3. The estimated results suggested that the optimal allocation of straw energy production structure was 40.10% for straw densification into briquette fuel production, 35.34% for straw power generation, 19.56% for straw gasification, and 5% for straw liquefaction.
4. The findings of this study will guide policy makers and investors to develop suitable straw energy technologies in Eastern China, and the research framework of this study can be applied to other regions or countries to aid the decision-making process for the development of relevant bioenergy industries.

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