Engineering and Technology Journal e-ISSN: 2456-3358
Volume 10 Issue 05 May-2025, Page No.- 5274-5287
DOI: 10.47191/etj/v10i05.56, I.F. – 8.482

Evaluation of Straw Recycling Programs Based on Evidence-Prospect Theory

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ABSTRACT: Farmland straw is one of the important agricultural resources, and its rational utilization is related to the green development of agriculture. In order to promote the utilization of straw resources, the rapid increase of market enterprises, the current choice of straw treatment methods is relatively rich, so it is particularly important to determine the appropriate comprehensive utilization of straw. To reduce the uncertainty and subjectivity of expert evaluation opinions, this paper uses the method of combining DS evidence theory and prospect theory to analyze the four methods of direct return, straw silage, incineration power generation and pyrolysis gasification, and constructs a clearer and more objective method evaluation system from the five dimensions of resources, technology, environment, economy and society. The DS evidence theory was used to integrate the information of multiple indicators, summarize and analyze the advantages and disadvantages of each scheme, evaluate and rank, and finally select the best treatment scheme. The results showed that pyrolysis gasification was the optimal solution for straw recycling, followed by incineration for power generation, followed by direct return to the field, and finally straw silage. The conclusion is that this method can improve the objectivity of the evaluation results to a certain extent, and put forward valuable suggestions for promoting the development of straw comprehensive utilization and sustainable agricultural development.

KEYWORDS: Dempster-Shafer Evidence Theory; Prospect Theory; Straw Comprehensive Utilization; evaluation index system; sustainable development

1. INTRODUCTION

China, as a major agricultural country, generates approximately 600-800 million tons of crop straw annually 12, with corn straw accounting for 200 million tons 3, representing 28.6% of the total. Straw serves not only as essential forage for herbivores but also as a "carbon-neutral" biomass energy source and a crucial component in agricultural-industrial value chains [4]. According to the *National Report on Comprehensive Utilization of Crop Straws* released by the Ministry of Agriculture and Rural Affairs, China's comprehensive straw utilization rate has steadily increased, maintaining over 86% in 2023. This forms a five-pronged utilization pattern dominated by fertilizerization (57.6%), feedization (20.7%), and energyization (8.3%). Annual straw returning quantities reach 400 million tons, with corn, rice, and wheat straw returning amounts of 126 million, 113 million, and 104 million tons respectively, corresponding to 42.6%, 66.5%, and 73.7% of their collectable yields. Rich in organic matter, NPK nutrients, and trace elements essential for crop growth [5], straw-derived organic components significantly improve soil structure, reduce chemical fertilizer dependency, and mitigate non-point source pollution. However, various utilization approaches present distinct characteristics: Fertilizerization primarily through direct incorporation enhances soil fertility but may release excessive organic carbon and nutrients over time, potentially exacerbating agricultural pollution [6,7]. For feedization, silage technology offers operational simplicity and low cost yet suffers from relatively low conversion efficiency [8]. In energy utilization, incineration-based power generation remains predominant but generates harmful emissions, causing environmental contamination and resource wastage [9]. While pyrolysis gasification demonstrates advantages in high resource recovery and zero secondary pollution, it faces industrial challenges including complex equipment and high investment costs [10-12]. This multidimensional utilization paradigm highlights straw's multifunctional role in ecological cycles while revealing urgent demands for technological innovation and industrial upgrading.

To promote the comprehensive utilization of crop straw, the Chinese government encourages nationwide implementation of demonstration projects to drive technological innovation and application, thereby enhancing straw resource utilization efficiency and economic benefits. Ensuring effective execution of these technologies necessitates the establishment of a scientific and standardized technical evaluation index system for precise screening and practical transformation of applicable technologies. Crucially, technology promotion urgently requires a multidimensional evaluation framework encompassing environmental benefits, economic viability, technical feasibility, social benefits, and resource recovery efficiency. This system not only enables scientific identification of regionally appropriate technologies but also provides decision-making support for differentiated regional applications, ultimately achieving synergistic advancement of green technology dissemination and sustainable agricultural development.

The selection of comprehensive straw utilization strategies constitutes a typical multi-attribute decision-making (MADM) problem, requiring balanced consideration of technical feasibility, economic returns, environmental impacts, and social benefits. Factors such as value perception and risk preferences significantly influence technology adoption decisions [13-16]. Dai Yaping [11] systematically reviewed biomass straw treatment technologies, summarizing prevalent processing methodologies. Currently, China predominantly employs three straw management approaches: direct field incorporation, incineration-based power generation, and composting [17].Zhu Liqun et al. [18] conducted a cost-benefit analysis comparing four utilization pathways – straw-to-feed conversion, straw-to-power generation, straw incorporation, and straw-to-biogas production – to evaluate their economic viability. Wang Hongyan et al. [19] applied emergy analysis to assess diverse manure utilization models. Yang Zengling et al. [20] implemented a grey relational ideal solution method integrating indicator weights and attribute values for optimized straw utilization scheme selection in Heilongjiang Province.Zhu Wen [21] employed a fuzzy analytic hierarchy process (FAHP)-based VIKOR approach to evaluate four straw-to-energy conversion modes in Jiangsu Province. Xian'en Wang et al. [22] combined principal component analysis (PCA) and autoregressive integrated moving average (ARIMA) modeling to estimate straw resource potential, quantitatively assessing regional energy-environment-social benefits of three bioenergy conversion technologies against Global Bioenergy Partnership (GBEP) sustainability indicators. Xu Zhaopeng [23] established five technical systems (feed, fertilizer, raw material, energy, and substrate utilization) based on nine typical Shandong models, evaluating them through emergy analysis. Song Baiyu [24] applied analytic hierarchy process (AHP)-entropy weight method to assess four straw utilization patterns in Shandong. Liang Meng et al. [25] performed technical-economic analysis on three large-scale straw utilization models using AHP, principal component projection, and grey relational analysis. M. Sun et al. [26] employed life cycle assessment (LCA) to evaluate environmental impacts of various wheat straw utilization approaches.

However, traditional decision-making methods exhibit limitations in addressing complex decision-making scenarios. During the evaluation process, decision-makers frequently encounter assessments involving hesitant and probabilistic information (e.g., experts' subjective judgments on criteria), which are often influenced by irrational preferences [27]. This necessitates decision models possessing dual capability in handling uncertainty and behavioral characteristics. In this context, the integration of evidence theory and prospect theory offers novel insights to resolve such challenges: The belief structure derived from evidence theory effectively manages uncertainty in experts' subjective evaluations across different selection criteria [28-30], serving as an indispensable tool for information fusion and decision analysis [31]. Meanwhile, prospect theory quantitatively characterizes decision-makers' risk preferences. The synergy between these frameworks simultaneously addresses enterprises' dual objectives of pursuing low-carbon environmental goals and maintaining economic viability in technology selection. The multi-attribute decision-making approach combining evidence reasoning and prospect theory [32] provides an effective solution for such complex scenarios. Therefore, constructing an evidence-prospect theoretical framework can deliver scientifically robust recommendations for selecting optimal straw utilization strategies, thereby advancing sustainable development in the biomass energy industry.

2.PRELIMINARIES

The methodological framework proceeds through three sequential phases: First, establishing a comprehensive evaluation system for straw utilization strategies; second, applying conventional Dempster-Shafer (DS) evidence theory to integrate multi-expert scoring data through information fusion; finally, constructing a prospect theory model to derive holistic multi-criteria evaluations for each treatment alternative. This integrated approach enables systematic comparison and performance ranking of different utilization schemes, thereby determining the optimal strategy through quantified decision analytics.

2.1Establishment of the Comprehensive Evaluation Indicator System

The evaluation system for comprehensive straw utilization schemes adopts a multi-level hierarchical structure comprising three layers: the objective layer, alternative layer, and indicator layer. Four straw utilization alternatives (A_1-A_4) are defined in the alternative layer: A_1 (direct straw returning), A_2 (straw silage production), A_3 (combustion for power generation), and A_4 (pyrolysis gasification). This framework systematically categorizes and classifies factors influencing current straw utilization scheme selection. Through expert surveys aligned with evaluation objectives and operational characteristics, critical evaluation indicators were identified. Guided by fundamental principles of economic efficiency, environmental sustainability, and social demand, a multi-criteria evaluation index system was ultimately established across five dimensions [33]: resource utilization, technological feasibility, environmental impact, economic viability, and social acceptability, as illustrated in Figure 1.

2.2. Evidence Theory

Dempster-Shafer (DS) Evidence Theory was first proposed by Dempster in 1967 [34], utilizing upper and lower probabilities to address multi-valued mapping problems. A series of seminal papers published subsequently formalized the theoretical framework. Later, G. Shafer, Dempster's student, advanced the theory by introducing belief functions, thereby establishing a mathematical system that processes uncertain reasoning through "evidence" and "combination." This framework not only emphasizes the objectivity of phenomena but also incorporates human subjectivity in evaluations, employing interval estimation to characterize uncertain information [35].

For a decision problem, let Θ represent the complete set of discernible outcomes, termed the frame of discernment[36, 37]. Each proposition corresponds to a subset of Θ. An item of evidence provides support to propositions through a basic probability assignment (BPA) m, defined as follows:

Let Θ be the frame of discernment. If a set function m: 2^Θ → [0,1] satisfies the following conditions:

$$m(\varnothing)=0$$

$$m(\alpha)=1$$

Then m is called a basic belief assignment (BBA) on the frame Θ. The value m(α) is termed the basic belief number (or basic belief mass) assigned to α.

A belief function represents the minimum confidence level in a proposition or hypothesis, quantified as the cumulative sum of all evidence supporting that proposition. It reflects our certainty about the occurrence of an event.

The relationship between the belief function and the plausibility function is as follows:

Given two independent pieces of evidence m_1 and m_2 , the combination rule in Dempster-Shafer (DS) evidence theory, denoted as $m=m_1\oplus m_2$,is defined by:

$$m(\alpha)=\begin{cases}\frac{1}{1-k}\sum_{\beta\cap\gamma}=m_1(\beta)m_2(\gamma),\alpha\neq\varnothing\\ 0\quad,\alpha=\varnothing\end{cases} \tag{1}$$

$$K=\sum_{\beta\cap\gamma=\alpha}m_1(\beta)m_2(\gamma) \tag{2}$$

In the formula, K is the conflict coefficient, which quantifies the degree of conflict between distinct pieces of evidence. Its value is positively correlated with the intensity of inter-evidence conflict. In traditional DS theory-based belief calculations, the direct application of the combination rule may yield counterintuitive results (e.g., in high-conflict scenarios). To address this limitation, scholars have proposed various improved algorithms. Among these, the weighted averaging method has emerged as a representative enhancement approach due to its computational simplicity and practical efficacy. This method achieves dynamic fusion of belief structures by incorporating adaptive weighting factors.

(1) Computing the arithmetic average of all belief structures:

$$\bar{m} = \frac{m_1 + \cdots + m_n}{n}$$

(2) Calculate the Euclidean distance between each piece of evidence and the average belief structure:

$$d_t = \|m_t - \bar{m}\| = \sqrt{(m_t(\alpha) - \bar{m}(\alpha))^2 + \cdots}$$

(3) Define the plausibility measure for evidence t:

$$s_t = 1 - d_t$$

(4) Normalize the plausibility measures to obtain weighting factors:

$$\omega_t = \frac{s_t}{\sum_{t=1,2,\ldots,n} s_t}, t = 1, 2, \ldots, n$$

(5) Compute the weighted average belief structure:

$$\bar{m}(B) = \sum_{t=1}^{n} \omega_t m_t(B), \forall B \subseteq \Omega$$

(6) Synthesize multiple pieces of evidence $m_1, m_2, \ldots, m_n$, using Dempster's combination rule:

$$m = [\ldots[m_1 \oplus m_2] \oplus \ldots \oplus m_n]$$

2.3 Prospect Theory

Prospect Theory, also known as decision-making theory under uncertainty, was proposed by psychologists Daniel Kahneman and Amos Tversky. It applies psychological research to economics and has made groundbreaking contributions to understanding human judgment and decision-making in uncertain contexts [38, 39]. In contrast to the long-standing rational actor hypothesis, Prospect Theory empirically reveals how non-rational psychological factors—rooted in human cognitive biases and behavioral traits—influence choice behavior.

In Prospect Theory, risk preferences are characterized by two components: the value function and the probability weighting function. The value function captures the decision-maker's subjective risk attitudes by evaluating gains and losses relative to a reference point. Outcomes above the reference point are perceived as gains (beneficial), while those below are perceived as losses [40, 41]. To reduce the subjectivity in reference point selection and align it with decision-making logic, we adopt the median value of 0.5 as the reference point. The value function is defined as:

$$v(\Delta x_u) = \begin{cases} (\Delta x_u)^{\alpha}, \Delta x_u \geq 0 \\ -\lambda(\Delta x_u)^{\beta}, \Delta x_u < 0 \end{cases}$$

In the formula,Δx represents the gain or loss value; α is the risk preference coefficient; β is the risk aversion coefficient; λ is the risk sensitivity coefficient. When λ>1, it indicates that decision-makers are more sensitive to losses. In prospect theory, decision-makers are more sensitive to losses than gains.

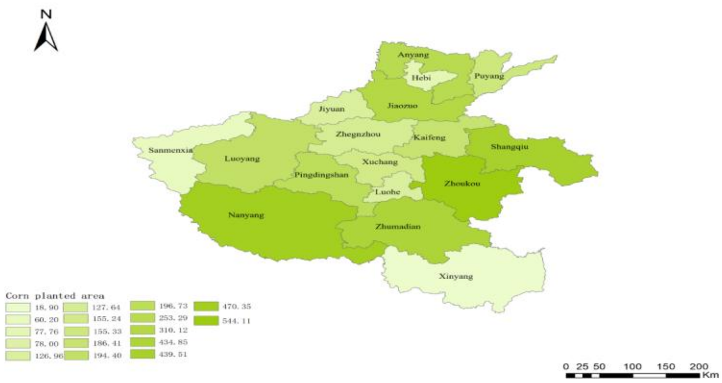
$$V = \sum v(\Delta x_u)$$

In the formula, V represents the total prospect value of the plan. Since the comprehensive utilization plan for straw cannot take risks into account, the probability decision weight in the prospect theory is not considered. When V is larger, it is believed that the prospect of the plan is better; when V is smaller, it is considered that the prospect of the plan is worse.

2.4 Study Area and Data Sources

2.4.1 Study Area

Henan Province, a major agricultural hub in China, is characterized by loess and clay soils highly suitable for crop cultivation. It contributes 9.3% of the national maize sown area and 9.0% of total maize production, earning its reputation as the "Central Plains Granary" [42]. The spatial distribution of maize straw yield across cities in Henan Province is illustrated in Figure 2.



2.4.2 Data Sources

The maize data for Henan Province from 2019 to 2023—including sown area and yield—were obtained from the Henan Statistical Yearbook published by the Henan Provincial Bureau of Statistics. Detailed values are provided in Table 1.

Table 1 Sown area and yield of maize

Year	Corn Sown Area (Thousand Hectares)）	Corn Production (10,000 Metric Tons)
2019	3801.33	2247.37
2020	3818.01	2342.37
2021	3865.78	2033.93
2022	3857.52	2275.05
2023	3864.07	2365.70

China has not yet established an official database for statistical monitoring of straw yield. Commonly used estimation methods include the Straw-to-Grain Ratio (SGR) method, Economic Coefficient Method, and Byproduct Percentage Method. In this study, we adopt the SGR method to estimate straw yield in Henan Province. The calculation formula is:

3 PROSPECT THEORY FRAMEWORK OF EVIDENCE

3.1 Decision Problem in Evidence Theory

Let A represent the decision matrix, whose factors consist of a finite number of options Ai and a finite number of criteria Cj, where i = 1,2,3,... Cj,... Cj,... Cj,... Cj. .. t and j = 1,2,3,... The plural form of "n".

$$A = \begin{matrix} & \begin{matrix} C_1 & \cdots & C_n \end{matrix} \\ \begin{matrix} A_1 \\ \vdots \\ A_t \end{matrix} & \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{t1} & \cdots & x_{tn} \end{bmatrix} \end{matrix}$$

To compare these comprehensive utilization schemes of straw, a set of language terms was defined, including five assessment grades ranging from "good" to "poor". These data are shown in Table 3.

Table 3 Evaluation set and fuzzy evaluation values

Evaluation symbol	V1	V2	V3	V4	V5
Value	1	2	3	4	5
Evaluation set	Good	Medium good	Medium	Medium poor	Poor

Multiple domain experts provide estimates for each criterion of every alternative, characterized by belief structures. Let the belief structure $C_{ij}^k(B_{ij}^k)$ proposed by expert k represent the evaluation value of alternative Ai under criterion Cj, where the focal element $C_{ij}^k(B_{ij}^k)$ given by expert k corresponds to a linguistic term set for Aiwith respect to Cj. The evaluation values of each alternative's criteria provided by the experts are presented in Table 4.

Table 4 Expert scores

	Index	Expert 1	…	Expert k	…	Expert n
A_1	C1	$C_{11}^1(B_{11}^1)$	…	$C_{11}^k(B_{11}^k)$	…	$C_{11}^n(B_{11}^n)$
	…	…	…		…	
	Cj	$C_{1j}^1(B_{1j}^1)$	…	$C_{1j}^k(B_{1j}^k)$	…	$C_{1j}^n(B_{1j}^n)$
	…	…	…	…	…	
	Cn	$C_{1n}^1(B_{11}^1)$	…	$C_{1n}^k(B_{11}^k)$	…	$C_{1n}^n(B_{11}^n)$
…	…	…	…	…	…	

Ai	C1	$C_{i1}^1(B_{i1}^1)$	…	$C_{ij}^k(B_{ij}^k)$	…	$C_{i1}^n(B_{i1}^n)$
	…	…	…	…	…	
	Cj	$C_{ij}^1(B_{ij}^1)$	…	$C_{ij}^k(B_{ij}^k)$	…	$C_{ij}^n(B_{ij}^n)$
	…	…	…	…	…	
	Cn	$C_{in}^1(B_{in}^1)$	…	$C_{in}^k(B_{in}^k)$	…	$C_{in}^n(B_{in}^n)$
…	…	…	…	…	…	
At	C1	$C_{t1}^1(B_{t1}^1)$	…	$C_{t1}^k(B_{t1}^k)$	…	$C_{t1}^n(B_{t1}^n)$
	…	…	…	…	…	…
	Cj	$C_{tj}^1(B_{tj}^1)$	…	$C_{tj}^k(B_{tj}^k)$	…	$C_{tj}^n(B_{tj}^n)$
	…	…	…	…	…	…
	Cn	$C_{tn}^1(B_{tn}^1)$	…	$C_{tn}^k(B_{tn}^k)$	…	$C_{tn}^n(B_{tn}^n)$

3.2 Combined Belief Structure

Assumes that there is a trust structure m_i,t = 1,2,... n, calculate the average structure of each trust structure as:

$$m_{is}^0(B_{is}^0)=\frac{m_{ij}^1(B_{ij}^1)+\cdots+m_{ij}^n(B_{ij}^n)}{n} \quad (4)$$

Calculate the distance between each piece of evidence and the average evidence:

$$d_J\left\|m_{ij}^k(B_{ij}^k)-m_{is}^0(B_{is}^0)\right\|=\sqrt{(m_{ij}^k(B_{ij}^k)-m_{is}^0(B_{is}^0))^2+\cdots} \quad (5)$$

The fidelity table of evidence mi is shown as:

$$Sim((m_{ij}^k(B_{ij}^k),m_{is}^0(B_{is}^0)))=1-d_J\left\|m_{ij}^k(B_{ij}^k)-m_{is}^0(B_{is}^0)\right\| \quad (6)$$

The greater the similarity between $C_{ij}^k(B_{ij}^k)$ and $C_{ij}^0(B_{ij}^0)$, the greater the support.

$$Sup(m_{ij}^k(B_{ij}^k))=\sum_{o=1,0\neq k}^{l} Sim(m_{ij}^k(B_{ij}^k),m_{is}^0(B_{is}^0)) \quad (7)$$

Finally, calculate the credibility of each piece of evidence, which is the weight:

$$\omega_{ij}^k(B_{ij}^k)=Sup(m_{ij}^k(B_{ij}^k))/\sum_{k=1}^{l}Sup(m_{ij}^k(B_{ij}^k)) \quad (8)$$

Given n belief structures $m_1,m_2,\ldots,m_n$, each assigned a weight factor w_t(t=1,2,…,n) such that $\sum w_t=1$. The weighted average belief structure is then expressed as:

$$\bar{m}(B)=\sum_{t=1}^{n}\omega_t m_t(B),\forall B\subseteq\Omega \quad (9)$$

In the formula: m- (B) is the average trust structure of proposition B; mt(B) is the t trust structure of proposition B; n is the number of trust structures. From $m_1,m_2,\ldots,m_n$, The final trust structure of mn synthesis is:

$$m=[\ldots[m_1\oplus m_2]\oplus\ldots\oplus m_n] \quad (10)$$

3.3 Prospect Theory

First, the relevant parameters in prospect theory are determined. The risk sensitivity coefficient for gains α = 0.88, the risk sensitivity coefficient for losses β = 0.88, and the loss aversion coefficient λ = 2.25, which quantifies the decision-maker's asymmetric loss aversion characteristics. The selection of the reference point is crucial in prospect theory-based MCDM. Outcomes below (above) the reference point are regarded as losses (gains). The fuzzy evaluation value "V3" is taken as the reference point, since such an evaluation grade implies a 0.5 probability criterion of being good or bad.

$$v(\Delta x_u)=\begin{cases}(\Delta x_u)^{\alpha},\Delta x_u\geq 0\\ -\lambda(\Delta x_u)^{\beta},\Delta x_u<0\end{cases} \quad (11)$$

$$V=\sum v(\Delta x_u) \quad (12)$$

Where V denotes the total prospect value of the alternative. As the straw comprehensive utilization alternatives cannot account for risk factors, the probability weighting function in prospect theory is excluded from consideration. A higher V value indicates more favorable prospects for the alternative, while a lower V value suggests less favorable prospects.

The evaluation process initiates with establishing an assessment index system for straw comprehensive utilization methods. Subsequently, Dempster-Shafer (DS) theory is employed to aggregate expert evaluations. The total prospect value for each treatment method is then computed based on prospect theory, followed by a comprehensive ranking of alternatives. The complete evaluation procedure is illustrated in Figure 3.

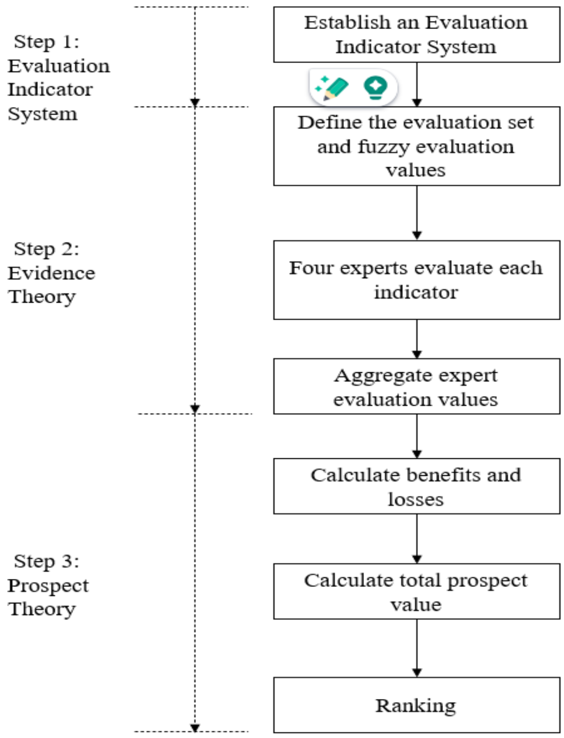


Fig 3 Evaluation process of comprehensive utilization of straw

Step 1: Establish an evaluation system for straw comprehensive utilization alternatives.

Step 2: Assess each alternative's indicators using belief structures provided by multiple experts.

Step 3: Fuse multi-expert evaluations using Dempster-Shafer (DS) evidence theory.

Step 4: Calculate gains and losses for each alternative based on prospect theory.

Step 5: Rank all alternatives using the obtained total prospect values.

4. A Case Study

4.1 Evaluation Indicator

The comprehensive utilization rate of crop straw in the province reached 93.89% in 2023 [44]. While various utilization methods for straw have advanced, some regions still face challenges with straw burning, leading to multi-day deterioration of ambient air quality and aggravated pollution [45]. This situation not only adversely impacts the environment but also poses safety hazards such as fire risks, resulting in substantial socioeconomic losses. Consequently, selecting appropriate comprehensive utilization methods for crop straw is critical. The primary barrier to effective straw utilization lies in technological limitations [46]. (See Table 5)

Table 5 Evaluation indicator system

Target Layer	Indicator Layer
Comprehensive Utilization Methods of Straw	Resource
	Technology
	Economy
	Environment
	Society

Based on the constructed evaluation indicator system, 10 experts were invited to assess each indicator by integrating their professional experience and knowledge. The evaluation set classifies assessment grades into five levels: Poor, Fair, Medium, Good, and Excellent, with each level corresponding to specific fuzzy evaluation values. The evaluation set and its associated fuzzy values are presented in Table 6. Each evaluation indicator is represented by a belief structure. Assessments of the second-level indicators were conducted by 10 experts, including scholars in agricultural management and practitioners engaged in comprehensive crop straw utilization, with the evaluation results summarized in Table 6.

Table 6 Evaluation set and fuzzy evaluation values

Evaluation set	Good	Medium good	Medium	Medium poor	Poor
Symbol	V1	V2	V3	V4	V5
Evaluation Value	0.9	0.7	0.5	0.3	0.1

4.2 Evaluation of Each Criterion for Each Straw Comprehensive Utilization Scheme

Experts evaluate the indicators for each straw comprehensive utilization scheme, where each indicator corresponds to a belief structure. As shown in Table 7, the belief structure (e.g., ({v_3}, 0.9; {v_4}, 0.1)) represents Expert 1's assessment of Scheme 1 (direct straw returning), indicating a 0.9 probability assigned to evaluation level {v_3} and a 0.1 probability to evaluation level {v_4}.

Table 7 Results of the assessment of the level 2 indicators by ten experts

	index	expert 1	expert 2	expert 3	expert 4	expert 5
	C1	{v3},0.2;{v4},0.8	{v3},0.5;{v4},0.5	{v3},0.3;{v4},0.7	{v3},0.6;{v4},0.4	{v3},0.3;{v4},0.7
	C2	{v2},0.3;{v3},0.7	{v2},0.6;{v3},0.4	{v2},0.9;{v3},0.1	{v2},0.1;{v3},0.9	{v2},0.3;{v3},0.7
A1	C3	{v2},0.6;{v3},0.4	{v2},0.5;{v3},0.5	{v2},0.6;{v3},0.4	{v2},0.1;{v3},0.9	{v2},0.5;{v3},0.5
	C4	{v2},0.6;{v3},0.4	{v2},0.1;{v3},0.9	{v2},0.7;{v3},0.3	{v2},1	{v2},0.5;{v3},0.5
	C5	{v3},0.6;{v4},0.6	{v3},0.1;{v4},0.9	{v3},0.6;{v4},0.4	{v3},0.1;{v4},0.9	{v3},0.4;{v4},0.6
	C1	{v3},0.9;{v4},0.1	{v3},0.4;{v4},0.6	{v3},0.7;{v4},0.3	{v3},0.6;{v4},0.4	{v3},0.6;{v4},0.4
	C2	{v2},0.3;{v3},0.7	{v2},0.2;{v3},0.8	{v2},0.6;{v3},0.4	{v2},0.5;{v3},0.5	{v2},0.4;{v3},0.6
A2	C3	{v2},0.1;{v3},0.9	{v2},0.7;{v3},0.3	{v2},0.4;{v3},0.6	{v2},0.5;{v3},0.5	{v2},1
	C4	{v2},0.3;{v3},0.7	{v2},0.1;{v3},0.9	{v2},1	{v2},0.4;{v3},0.6	{v2},0.1;{v3},0.9
	C5	{v3},0.7;{v4},0.3	{v3},0.6;{v4},0.4	{v3},0.7;{v4},0.3	{v3},0.1;{v4},0.9	{v3},0.3;{v4},0.7
	C1	{v3},0.9;{v4},0.1	{v3},0.2;{v4},0.8	{v3},0.7;{v4},0.3	{v3},0.4;{v4},0.6	{v3},0.1;{v4},0.9
	C2	{v2},0.7;{v3},0.3	{v2},0.2;{v3},0.8	{v2},0.7;{v3},0.3	{v2},0.8;{v3},0.2	{v2},0.6;{v3},0.4
A3	C3	{v2},0.3;{v3},0.7	{v2},0.5;{v3},0.5	{v2},0.9;{v3},0.1	{v2},0.8;{v3},0.2	{v2},0.6;{v3},0.4
	C4	{v2},0.6;{v3},0.4	{v2},0.7;{v3},0.3	{v2},0.5;{v3},0.5	{v2},1	{v2},0.9;{v3},0.1
	C5	{v3},0.3;{v4},0.7	{v3},0.5;{v4},0.5	{v3},0.6;{v4},0.4	{v3},0.1;{v4},0.9	{v3},0.8;{v4},0.2
	C1	{v3},0.7;{v4},0.3	{v3},0.6;{v4},0.4	{v3},0.3;{v4},0.7	{v3},0.6;{v4},0.4	{v3},0.8;{v4},0.2
	C2	{v2},0.3;{v3},0.7	{v2},0.4;{v3},0.6	{v2},0.9;{v3},0.1	{v2},0.2;{v3},0.8	{v2},0.4;{v3},0.6
A4	C3	{v2},0.8;{v3},0.2	{v2},0.7;{v3},0.3	{v2},0.2;{v3},0.8	{v2},0.4;{v3},0.6	{v2},0.5;{v3},0.5
	C4	{v2},0.5;{v3},0.5	{v2},0.6;{v3},0.4	{v2},1	{v2},0.6;{v3},0.4	{v2},0.3;{v3},0.7
	C5	{v3},0.5;{v4},0.5	{v3},1	{v3},0.6;{v4},0.4	{v3},0.1;{v4},0.9	{v3},0.9;{v4},0.1

	index	expert 6	expert 7	expert 8	expert 9	expert 10
	C1	{v3},0.2;{v4},0.8	{v3},1	{v3},0.2;{v4},0.8	{v3},0.4;{v4},0.6	{v3},0.6;{v4},0.4
	C2	{v2},0.7;{v3},0.3	{v2},0.8;{v3},0.2	{v2},0.4;{v3},0.6	{v2},1	{v2},0.2;{v3},0.8
A1	C3	{v2},0.7;{v3},0.3	{v2},0.4;{v3},0.6	{v2},1	{v2},0.7;{v3},0.3	{v2},0.2;{v3},0.8
	C4	{v2},0.4;{v3},0.6	{v2},0.5;{v3},0.5	{v2},0.1;{v3},0.9	{v2},0.3;{v3},0.7	{v2},0.3;{v3},0.7
	C5	{v3},0.1;{v4},0.9	{v3},0.3;{v4},0.7	{v3},0.1;{v4},0.9	{v3},0.9;{v4},0.1	{v3},0.1;{v4},0.9
	C1	{v3},0.3;{v4},0.7	{v3},0.4;{v4},0.6	{v3},0.2;{v4},0.8	{v3},0.3;{v4},0.7	{v3},0.1;{v4},0.9
	C2	{v2},0.4;{v3},0.6	{v2},0.1;{v3},0.9	{v2},0.4;{v3},0.6	{v2},0.7;{v3},0.3	{v2},1
A2	C3	{v2},0.4;{v3},0.6	{v2},0.8;{v3},0.2	{v2},0.4;{v3},0.6	{v2},0.5;{v3},0.5	{v2},0.4;{v3},0.6
	C4	{v2},0.2;{v3},0.8	{v2},0.6;{v3},0.4	{v2},0.9;{v3},0.1	{v2},0.8;{v3},0.2	{v2},0.3;{v3},0.7
	C5	{v3},0.1;{v4},0.9	{v3},0.6;{v4},0.4	{v3},0.3;{v4},0.7	{v3},0.1;{v4},0.9	{v3},0.5;{v4},0.5
	C1	{v3},1	{v3},0.4;{v4},0.6	{v3},0.8;{v4},0.2	{v3},0.8;{v4},0.2	{v3},0.3;{v4},0.7
	C2	{v2},1	{v2},0.4;{v3},0.6	{v2},0.8;{v3},0.2	{v2},0.8;{v3},0.2	{v2},0.6;{v3},0.4
A3	C3	{v2},0.4;{v3},0.6	{v2},0.5;{v3},0.5	{v2},1	{v2},0.4;{v3},0.6	{v2},0.3;{v3},0.7
	C4	{v2},0.7;{v3},0.3	{v2},0.8;{v3},0.2	{v2},0.3;{v3},0.7	{v2},0.1;{v3},0.9	{v2},0.8;{v3},0.2
	C5	{v3},0.1;{v4},0.9	{v3},1	{v3},0.4;{v4},0.6	{v3},0.2;{v4},0.8	{v3},0.9;{v4},0.1
	C1	{v3},0.2;{v4},0.8	{v3},0.7;{v4},0.3	{v3},1	{v3},0.5;{v4},0.5	{v3},0.9;{v4},0.1
	C2	{v2},1	{v2},0.7;{v3},0.3	{v2},0.5;{v3},0.5	{v2},0.2;{v3},0.8	{v2},0.2;{v3},0.8
A4	C3	{v2},0.2;{v3},0.8	{v2},1	{v2},0.4;{v3},0.6	{v2},0.5;{v3},0.5	{v2},0.4;{v3},0.6
	C4	{v2},0.9;{v3},0.1	{v2},0.1;{v3},0.9	{v2},0.7;{v3},0.3	{v2},0.8;{v3},0.2	{v2},0.9;{v3},0.1
	C5	{v3},0.5;{v4},0.5	{v3},0.4;{v4},0.6	{v3},0.9;{v4},0.1	{v3},0.5;{v4},0.5	{v3},0.1;{v4},0.9

4.3. Fusion of Evaluations

Based on Eqs. (9)-(10), the fusion results of each secondary-level indicator can be obtained. According to the quantified assessment linguistic terms provided by the evaluation experts, the final evaluation results for each indicator are derived as shown in Table 9:

Table 9 Fusion results of the evaluation of the level 2 indicators

	index	Final Aggregated Evaluation	Evaluation Result
A_1	C1	{v3},0.0123;{v4},0.9877	0.3025
	C2	{v2},0.0267;{v3},0.8578	0.6025
	C3	{v2},0.8003;{v3},0.1997	0.6601
	C4	{v2},0.0561;{v3},0.9439	0.5112
	C5	{v3},0.0275;{v4},0.9725	0.3000
A_2	C1	{v3},0.0687;{v4},0.9313	0.3137
	C2	{v2},0.0643;{v3},0.9357	0.5129
	C3	{v2},0.4950;{v3},0.5050	0.599
	C4	{v2},0.05;{v3},0.95	0.51
	C5	{v3},0.0202;{v4},0.9798	0.304
A_3	C1	{v3},0.9285;{v4},0.0715	0.4857
	C2	{v2},0.9995;{v3},0.0005	0.6999
	C3	{v2},0.8504;{v3},0.1496	0.6701
	C4	{v2},0.9993;{v3},0.0007	0.6999
	C5	{v3},0.2053;{v4},0.7947	0.3411
A_4	C1	{v3},0.9971;{v4},0.0029	0.4994
	C2	{v2},0.0665;{v3},0.9335	0.5133

C3	{v2},0.8003;{v3},0.1997	0.5697
C4	{v2},0.9991;{v3},0.0009	0.6998
C5	{v3},0.8673;{v4},0.1327	0.4735

Values below 0.0001 are omitted as they are deemed negligible for influencing the final results.

Following the same procedure, the fusion and quantification of all secondary-level indicators yield the results shown in Table 10.

Table 10 Level 1 indicators evaluate the fusion results

	Final Aggregated Evaluation	Evaluation Result
A1	{v2},0.0002;{v3},0.9903;{v4},0.0095	0.4981
A2	{v2},0.0014;{v3},0.9736;{v4},0.0251	0.4953
A3	{v2},0.9999;{v3},0.0001	0.7
A4	{v2},0.0041;{v3},0.9959	0.5008

4.4 Prospect Theory Decision-Making

When the weight vectors of all attributes are equal, the aggregated evaluation results from Table 9 are substituted into Equation (11). The parameters of the value function are set as follows: $\lambda = 2.25$, $\alpha = 0.88$, $\beta = 0.88$ [47]. Since the reference point significantly influences decision-making, it is critical to select an appropriate reference point. Results above the reference point are perceived as gains, while those below are regarded as losses. With the reference point set at 0.5 (the median score), the positive and negative prospect values for each secondary indicator were obtained, as shown in Table 11.

Table 11 Value function

Level 1 Indicators	Resource	Technology	Economy	Environment	Society
A_1	-0.5399	0.1347	0.1995	0.0192	-0.5459
A_2	-0.5128	0.0217	0.1307	0.0174	-0.5363
A_3	-0.0536	0.2425	0.2104	0.2425	-0.4458
A_4	-0.0033	0.0223	0.0959	0.2424	-0.0922

As indicated in the table above, the pyrolysis gasification technology demonstrates strong benefits in improving straw resource utilization and reducing environmental pollution, but lags slightly in economic benefits. In contrast, straw combustion for power generation holds significant economic advantages over other disposal methods. Combustion for power generation, straw silage, and pyrolysis gasification all generate substantial social benefits by promoting employment and driving socioeconomic development.

A comparative analysis of the benefits of the four straw utilization schemes across different dimensions is shown in Figure 4. Direct straw return to fields performs poorly in economic benefits. Combustion for power generation exhibits clear advantages in economic and social benefits, while pyrolysis gasification excels in environmental performance but underperforms economically

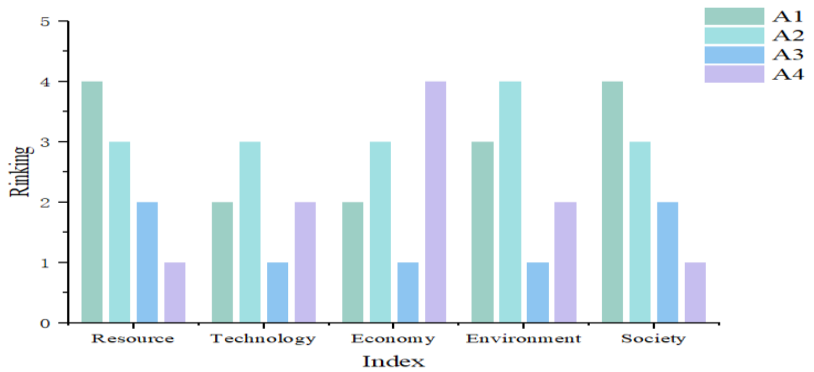


Fig 4 Comparison of various indicators of straw recycling program

The total prospect values of each scheme were calculated using Equation (12) to identify the optimal solution, as summarized in Table 12.

Table 9 Overall outlook values for each scenario

Scheme	Total Prospect Value	Ranking
A_1	-0.7324	3
A_2	-0.8793	4
A_3	0.196	2
A_4	0.2651	1

As shown in Table 12, the total prospect values of the four disposal schemes are calculated by summing the positive and negative prospect values of each indicator. The total prospect values for the four schemes are -0.7324, -0.8793, -0.196, and -2651, respectively. These values reflect the comprehensive evaluation of each disposal scheme across multiple criteria. Based on this analysis, Scheme 4 is identified as the optimal solution, followed by Scheme 3, then Scheme 1, with Scheme 2 performing the least favorably.

4.5 Comparative Analysis

In order to better understand the comparison results, Figure 5 shows the ranking order of these schemes.

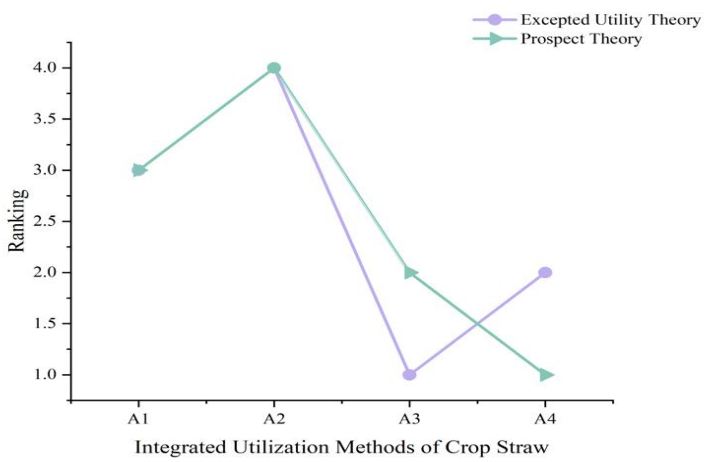


Fig 5 Ranking of schemes

The ranking orders of straw comprehensive utilization schemes derived from these two methods exhibit significant differences. The evidential prospect theory framework identifies A4 (pyrolysis gasification) as the most optimal recommendation, whereas the DS theory prioritizes A3 (combustion for power generation). This discrepancy arises primarily because results based on the evidential prospect theory framework align more closely with decision-makers' practical experience, while the DS theory fails to account for their irrational behaviors (e.g., risk aversion or preference distortion). In summary, compared to these two methods, the evidential prospect theory framework yields superior final decision outcomes by effectively capturing the non-rational decision-making tendencies of stakeholders.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In recent years, the comprehensive utilization of crop straw has developed rapidly. However, environmental pollution caused by improper straw disposal persists, making the selection of appropriate utilization methods critically important. This study evaluates four comprehensive utilization schemes in Henan Province—direct return to fields, silage production, combustion for power generation, and pyrolysis gasification—by constructing an evaluation system encompassing five dimensions: resources, technology, environment, economy, and society. Using the prospect theory framework, the four schemes were comprehensively assessed, with total prospect values ranked accordingly. Results indicate that straw pyrolysis gasification achieved the highest total prospect value, representing the optimal choice. This conclusion provides a reference for sustainable straw utilization in Henan Province. By ranking schemes through comprehensive prospect values, decision-making outcomes better reflect decision-makers' bounded rationality, ensuring alignment with practical realities.

The methodology has limitations, primarily its reliance on domain experts. To advance straw utilization, future research should establish a more comprehensive and scientific multi-level evaluation index system that incorporates additional influencing factors, such as policy support and transportation/storage conditions, to enhance evaluation rigor. Integrating neural network analysis could enable deeper exploration of straw utilization patterns and promote sustainable agricultural development. The proposed method demonstrates strong adaptability and can be extended to evaluate crop straw utilization across different regions.

5.2 Policy Recommendations

The utilization of straw resources should establish a diversified promotion mechanism tailored to local conditions. It is recommended to strengthen the implementation path from three dimensions: Firstly, improve the policy support system. Establish incentive mechanisms such as rewarding instead of subsidizing and special support. Focus on cultivating new agricultural business entities to form a demonstration effect, and build a circular utilization model of "driven by large households + promotion of technology".

Secondly, innovate the way of publicity and guidance. Utilize the new media matrix to carry out visual communication. Through carriers such as short videos and technical live broadcast classes, visually demonstrate to farmers the economic, environmental and social benefits of the "five utilization methods" of straw, and reverse the traditional mindset of burning straw. Issue relevant honors to farmers who actively participate in straw utilization to enhance their social recognition. Let more people understand the concepts, technologies and benefits of using straw to produce biogas from agricultural crops, and enhance the awareness of all sectors of society about comprehensive straw utilization methods.

In addition, satellite remote sensing and Internet of Things technologies can be used to monitor the distribution and utilization progress of straw, issue real-time warnings of burning risks, and optimize resource allocation

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