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# Reimagining carbon emission mitigation in sustainable agriculture: uncovering farmers' propensity for straw recycling

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The issue of carbon emission reduction for sustainable agriculture in rural areas has gained significant attention in China. Farmers play a crucial role as key implementers and active participants in this process, highlighting the significance of their awareness of carbon emission reduction. Straw, as the primary source of carbon emissions in rural areas, is a key component of rural carbon emission reduction efforts. This study focuses on 26 representative villages in Heilongjiang Province to analyze the current status of straw production and resource utilization in the context of rural carbon emission reduction. By employing the planned behavior theory in combination with structural equation modeling, the study aims to explore the analysis and prediction of farmers' willingness to reduce carbon emissions. The findings reveal that maize and rice crops are the primary sources of straw in Heilongjiang Province, with the existing policies primarily focusing on the practice of returning straw to the field. However, the burning of straw in the field remains prevalent due to factors such as immature conversion technologies, high costs, low benefits, and limited recycling rates of enterprises, subsequently leading to increased carbon emissions. Moreover, farmers' habits of stacking or burning straw in the field significantly influence straw utilization and carbon emission reduction awareness. To address these issues, the government should formulate appropriate straw recycling policies based on the specific circumstances and needs of farmers. Additionally, implementing comprehensive straw utilization policies becomes more effective when farmers have positive perceptions and awareness of carbon emission reduction and straw recycling. In conclusion, the government should develop diverse modes of straw resource utilization and field management tailored to local conditions. Furthermore, strengthening research and development efforts, providing technical training, and offering policy support are essential for promoting carbon emission reduction in rural areas.

KEYWORDS

**sustainable agriculture, carbon emission reduction, behavior intention, planned behavior theory, structural equation model**

## 1 Introduction

China's Carbon emissions in 2020 reached a staggering 9,894 Mt., accounting for roughly 30.7% of global emissions (Zhang et al., 2022). China, as the leading developing nation, recognizes the importance of reducing carbon emissions and has set ambitious goals to reach a peak in emissions based on energy consumption by 2030 and achieve carbon neutrality by 2060. Cropland plays a crucial role in the Earth's carbon cycle, acting as either a carbon sink or source for ecosystem carbon exchange (Yan et al., 2021). Over the past two decades, non-$CO_2$ greenhouse gas emissions from agricultural sources in China have increased significantly by approximately 37% (Chen et al., 2022). In 2015, agriculture accounted for around 50% of global non-$CO_2$ emissions (Le Quéré et al., 2018; Chen et al., 2022). The production process of agriculture contributes substantially to carbon emissions, primarily through waste products such as crop straw (Lee et al., 2020). Effective waste management of these solid wastes largely falls on the farmers' responsibility.

The production of crop straw in China has been increasing due to the rise in grain production, particularly in Heilongjiang Province, which is known as China's granary (Zhang et al., 2019). However, the distribution of straw is widespread and presents challenges in terms of unified management. This has led to an increased risk of improper disposal and open burning, which is a significant issue (Wen et al., 2020). In recent years, there have been improvements in rural economic levels and changes in energy structures, resulting in a gradual decrease in the utilization of straw as household fuel and feed (Wang S. et al., 2021; Wang et al., 2022). Despite the government's efforts to impose stricter penalties for open burning, this harmful practice continues to persist. In 2017, Heilongjiang Province alone produced 76.03 million tons of straw from main crops such as corn, rice, and beans, of which 3.921 million tons were burned openly. These open burning episodes release significant amounts of pollutants, including 38,000 tons of $PM_{10}$, 37,000 tons of $PM_{2.5}$, 121,000 tons of CO, and 8,000 tons of $N_2O$ (Cui et al., 2021). The burning of straw not only squanders valuable biomass resources but also contributes to the continuous decline in soil organic matter and the degradation of cultivated land quality. Moreover, it contributes to climate warming and environmental pollution, posing substantial risks to property and personal safety.

The comprehensive utilization of agricultural straw waste in China encounters various challenges (Wang et al., 2019; Afonso et al., 2021). Technical obstacles hinder the progress of straw recycling in sectors such as feed, energy, and industries (Espinosa et al., 2019; Lyu et al., 2020; Morsy et al., 2022). These challenges involve the high costs of recycling and the limited benefits it brings. Moreover, the widespread adoption of more efficient and cost-effective straw recycling technologies has not yet been accomplished (Song et al., 2017). Consequently, there has been limited advancement in enhancing China's overall capacity for crop straw recycling.

Recent research on farmers' disposal and reuse of crop straws has mainly focused on policy development and analyzing the current social status quo (Hellsten et al., 2019; Wang Y. et al., 2021; Smidt et al., 2022). The policies of national support have partially alleviated the proliferation of environmental pollution in agriculture. Nevertheless, hierarchical policy frameworks frequently lack a thorough comprehension of the cognitive steps farmers undertake in determining whether to make use of straw resources. Additionally, they fail to account for the diverse array of factors that can influence farmers' decision-making in this context. The issue of whether farmers can acknowledge themselves as the principal agents in reducing carbon emissions is pivotal, and the degree of behavioral consciousness among farmers holds paramount significance (He et al., 2022; Qiu et al., 2022). In the exploration of behavioral intention, Structural Equation Modeling (SEM) stands out as a systematic and efficacious research approach. Azmoodeh et al. delved into the effects of transportation planning on the capacity of urban residents using SEM (Azmoodeh et al., 2023). Similarly, Long et al. applied SEM to scrutinize energy-saving behavior among residents, uncovering the potential influence of economic and environmental factors on such behavior (Long et al., 2023). To address the practical challenges associated with straw disposal in specific regions and the internal factors influencing farmers' decisions, policymakers can formulate effective strategies by integrating these aspects.

This study seeks to analyze varying years and grain crop straw yields in Heilongjiang Province, estimate coefficients for pollutant emission factors, investigate the emission inventory of air pollution, and assess the potential energy utilization from the open burning of major crop straws in the region. A sampling survey method was deployed to select villages with extensive planting areas among the 12 prefecture-level cities in Heilongjiang Province as sample sites, aiming to scrutinize the current state of straw production and utilization. The study delves into the objective challenges associated with straw recycling among farmers. It employs a combination of planning behavior theory and the structural equation model to analyze factors influencing farmers' willingness to recycle and utilize straw. Finally, the research proposes a strategy for advancing the disposal and resource utilization of straw, offering a valuable reference for rural carbon emission reduction in Heilongjiang Province.

## 2 Experiments

### 2.1 Questionnaire design and recovery

Heilongjiang Province was chosen as the survey location, and its primary crops include corn, rice, soybeans, and wheat. In 2018, the annual crop straw production in Heilongjiang Province amounted to approximately 130 million tons, constituting roughly one-eighth of the national total (Fang et al., 2019), making it the leading province in China for straw production. For this research, we selected twelve villages with substantial agricultural acreage in the cities of Harbin, Qiqihar, Jixi, Hegang, Shuangyashan, Daqing, Yichun, Jiamusi, Qitaihe, Mudanjiang, Heihe, and Suihua within Heilongjiang Province, considering the distribution patterns of planting areas in the province as our survey sample locations. In the initial phase, we conducted a preliminary survey and subsequently refined our questionnaire. The questionnaire is structured into two primary sections. The first section gathers demographic data from farmers, including age, gender, educational background, and other relevant information. The second section delves into the Theory of Planned Behavior (TPB) as it pertains to farmers, encompassing multiple observable variables within each structural component. The questionnaire employs a five-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree), to gauge the extent of farmers' inclination toward straw recycling and utilization (Heo et al., 2022). Within this framework, the Use Habit (UH) component primarily reflects the actor's evaluation of the habitual nature of the behavior. Perceived Behavior Control (PBC) primarily encapsulates the actor's perception of the difficulty associated with executing a specific behavior. Subject Norm (SN) assesses the influence on an individual's decision to engage in a particular behavior. Finally, Behavioral Intention (BI) encompasses an actor's attitude and the influence it exerts on their inclination to engage in a specific behavior. It results from the combined impact of the subjective norm regarding the behavior and the perceived behavior control (Weber et al., 2020). Based on this theoretical model, we formulate the following hypotheses for subsequent verification and analysis (Coskun and Yetkin Ozbuk, 2020; Wang Q. et al., 2021).

> *H*1. Use habit affects perceived control.
>
> *H*2. Perceived control affects subjective norms.
>
> *H*3. Subjective norms affects behavioral intentions.
>
> *H*4. Subjective norms affects economic costs.
>
> *H*5. Economic costs affects behavioral intentions.

In this survey, a total of 500 questionnaires were distributed across representative villages in each city. Out of these, 479 questionnaires were successfully collected. After meticulous scrutiny, questionnaires exhibiting issues such as contradictions and incomplete information were excluded from the analysis, resulting in a dataset of 450 valid questionnaires. This yielded a questionnaire recovery rate of 90%, which satisfied the sample requirements (Yang et al., 2020). To conduct the questionnaire analysis, Microsoft Excel was utilized to tabulate the objective factors associated with farmers' straw disposal and utilization. Furthermore, the SPSS software, employing a cross-analysis method, was employed to examine the relationship between these two variables. In order to ensure the reliability and stability of our empirical findings, SPSS 24.0 was employed to assess the questionnaire's reliability and validity (Fu et al., 2019). The Kaiser Meyer Olkin (KMO) test was employed to evaluate the correlation between variables. A strong correlation is indicated when the partial correlation coefficient is significantly smaller than the simple correlation coefficient. In our study, the KMO value was calculated to be 0.64, surpassing the recommended threshold of 0.6, signifying its suitability for factor analysis. Moreover, Bartlett's test yielded a highly significant value of $p < 0.001$, further supporting the appropriateness of our dataset for factor analysis. Additionally, the Cronbach's coefficient value was determined to be 0.9, well above the acceptable threshold of 0.6, indicating that the questionnaire design was reasonably robust, and the data exhibited a high level of reliability and trustworthiness.

## 2.2 Structural equation model

Structural equation model (SEM) was used to analyze farmers' straw resource utilization behavior and influencing factors (Laksono et al., 2022). SEM is a statistical method to analyze the relationship between variables based on their covariance matrix. The model is as follows:

$$\eta = B\eta + \Gamma\xi + \xi \tag{1}$$

$$y = \Lambda y\eta + \varepsilon \tag{2}$$

$$x = \Lambda x\xi + \delta \tag{3}$$

In the formula, $\eta$ is the endogenous latent variable; $B$ is the relationship between the endogenous latent variables; $\Gamma$ is the influence of the exogenous variable on the endogenous variable; $\xi$ is the exogenous latent variable; $y$ is the endogenous variable; › $\boldsymbol{y}$ is the endogenous variable factor loading matrix on; $x$ is the exogenous variable; › $\boldsymbol{x}$ is the factor loading matrix on the exogenous variable; $\zeta$ , $\delta$ and $\varepsilon$ are error terms.

## 2.3 Straw resource estimation and coefficient determination

The economic yield (C) and straw coefficient (k), which represents the grass-to-valley ratio, for crops in different regions of Heilongjiang Province are derived from data provided by the Chinese government's statistics department and the statistical bureaus at both provincial and municipal levels. Reference data regarding the grass-to-valley ratio in Heilongjiang is presented in Supplementary Table S1. The formula for calculating the quantity of straw resources (Y) is expressed as follows (Fang et al., 2019).

$$Y_j = \sum\nolimits_{n=1}^{j} C_n \times K_n \tag{4}$$

In the formula, $Y_j$ represents the total amount of straw resources produced by j crops in the current year; j represents the total number of types of crops counted; n represents the types of crops; $C_n$ represents the economic output of n crops in the current year; $k_n$ represents the corresponding straw coefficient of n crops.

## 2.4 Pollutant and energy potential estimation for straw open burning

Pollutant emissions from open burning of corn, rice, wheat and soybean straw crops were investigated (Li L. et al., 2019; Li R. et al., 2019). The pollutant emissions from open burning of straw in the field are calculated using the following formula:

$$E = \sum\nolimits_{n=1}^{j} Y_j \times EF_n \times B \tag{5}$$

Within the formula, Yj represents the total amount of straw resources produced by j crops in the current year. E signifies the pollutant emission, while Fn denotes the emission factor of n types of crops. As for B, it represents the open burning efficiency.

The emission factors (EFs) for various pollutants present in crop straw are provided in Table 1. These EFs were determined through

TABLE 1 Emission factors for crop residues open burning.

| Crop | $PM_{10}$ | $PM_{2.5}$ | VOCs | $NH_3$ | $NO_X$ | $SO_2$ | $CH_4$ | CO | $CO_2$ |
|---|---|---|---|---|---|---|---|---|---|
| Rice (g/kg) | 5.78 | 13 | 6.1 | 0.8 | 3.1 | 0.9 | 3.2 | 30 | 1,460 |
| Wheat (g/kg) | 11.95 | 7.6 | 7.8 | 0.5 | 3.4 | 0.8 | 3.4 | 64.2 | 1,460 |
| Corn (g/kg) | 7.73 | 11.7 | 10.4 | 0.7 | 4.3 | 0.4 | 4.5 | 54 | 1,350 |
| Soybean (g/kg) | 6.93 | 3.3 | 8.7 | 0.5 | 1.1 | 0.3 | 3.9 | 33.5 | 1,445 |

local measurements or experiments involving the open burning of various types of straw. The collection of EFs from grains mainly includes EFs of pollutants such as $PM_{2.5}$, $PM_{10}$, VOCs, $NH_3$, $NO_X$, $SO_2$, CO and $CO_2$ (Wang et al., 2010). In our research, we employ the measurement of electricity output as a proxy to gauge the level of industrial activity or energy consumption. Given the substantial correlation between energy consumption and carbon emissions, the incorporation of electricity output as a variable enables us to precisely assess its influence on carbon emissions. By investigating this relationship, we can obtain a comprehensive understanding of the factors that contribute to carbon emissions and devise potential strategies for their mitigation.

The theory of potential energy (TEP) is calculated by multiplying the low heating value (LHV) of various crops and the corresponding straw yield. The formula is as follows:

$$\mathrm{TEP} = \sum\nolimits_{crop} LHV \times Y_{straw} \tag{6}$$

$$\mathrm{F} = \frac{\eta \times TEP}{100} \tag{7}$$

In the formula, $Y_{straw}$ is the crop straw yield, t; LHV is the theoretical potential energy (16.02 MJ/kg for rice; 12.38 MJ/kg for corn, soybean and wheat); F is the electricity output, TWh; H is the biomass power generation efficiency of the power plant; TEP is Theoretical Energy Potential, PJ.

The emission factor method is used to calculate the emission inventory of civil scattered coal combustion. The calculation formula of pollutant emission is as follows:

$$E_i = \frac{\sum_m A_m \times EF_{i,m}}{1000} \tag{8}$$

In the formula, $E_i$ is the emission of pollutant i, t; m is the coal type; $A_m$ is the activity level of coal type m, t; $EF_{i,m}$ is the emission factor, kg/t; The emission factors of coal combustion were shown in Supplementary Table S2.

# 3 Results and discussions

## 3.1 Crop straw production

Figure 1 illustrates the crop straw output in Heilongjiang Province between 1996 and 2018. This increase in straw production can be attributed to China's agricultural reform, which has led to a year-on-year rise in straw output in tandem with increased crop production. During the period from 1996 to 1999, the trend in crop straw production remained relatively steady. However, from 2000 to 2003, there was a four-year period of decline in China's straw production. The primary reason for this drop in grain output during 2000–2003 was the high cost associated with grain cultivation, which resulted in reduced enthusiasm among farmers for planting grains. Since 2004, a series of favorable measures for farmers, including the abolition of agricultural taxes and advancements in scientific farming techniques, have been implemented. These measures have significantly contributed to the rebound in straw production (Chen et al., 2021; Bai et al., 2022). In the rural agricultural reform initiated after 2004, the government increased investments in crop cultivation areas and effectively supported farmers in enhancing their production and farming processes. With government assistance, Chinese farmers rapidly improved their economic conditions, resulting in a substantial increase in grain production. This, in turn, led to a consistent annual rise in straw output. To summarize, since 1996, China's straw production has experienced substantial growth, mainly due to agricultural reforms and government support. Consequently, the management and resource utilization of straw have become significant components of rural environmental issues.

Since 2004, the production of straw in Heilongjiang Province has experienced a rapid surge, culminating in 2011 when it surpassed Henan Province to become the leading producer of crop straw. According to data from the "Heilongjiang Statistical Yearbook," the output of various crops between 2004 and 2018 was computed using Formula (4), as depicted in Figure 2. Notably, corn and rice straw exhibited significant outputs, while wheat, sorghum, and potato straw showed comparatively lower yields. The agricultural landscape in Heilongjiang Province is conducive to the cultivation of rice and corn. Rice straw production has demonstrated relative stability over the years, whereas corn straw output has exhibited a continuous upward trend, eventually surpassing that of rice straw. Conversely, the production of wheat straw has been in decline. In light of these trends, it becomes imperative to explore effective technologies for the management of corn and rice straw in the future.

## 3.2 Straw disposal and utilization

### 3.2.1 Survey respondents' background

The findings of the random survey revealed a male-to-female ratio in farm households close to 3:2, with males being the predominant gender. Peasant households are predominantly aged between 40 and 49 years (28.8%) and over 50 years (39.5%), indicating a serious issue of rural aging and a predominant agricultural labor force composed of middle-aged and elderly individuals. Educational attainment among farmers varies, with 34.4% having a junior high school education and 47.9% having a primary school education or below,

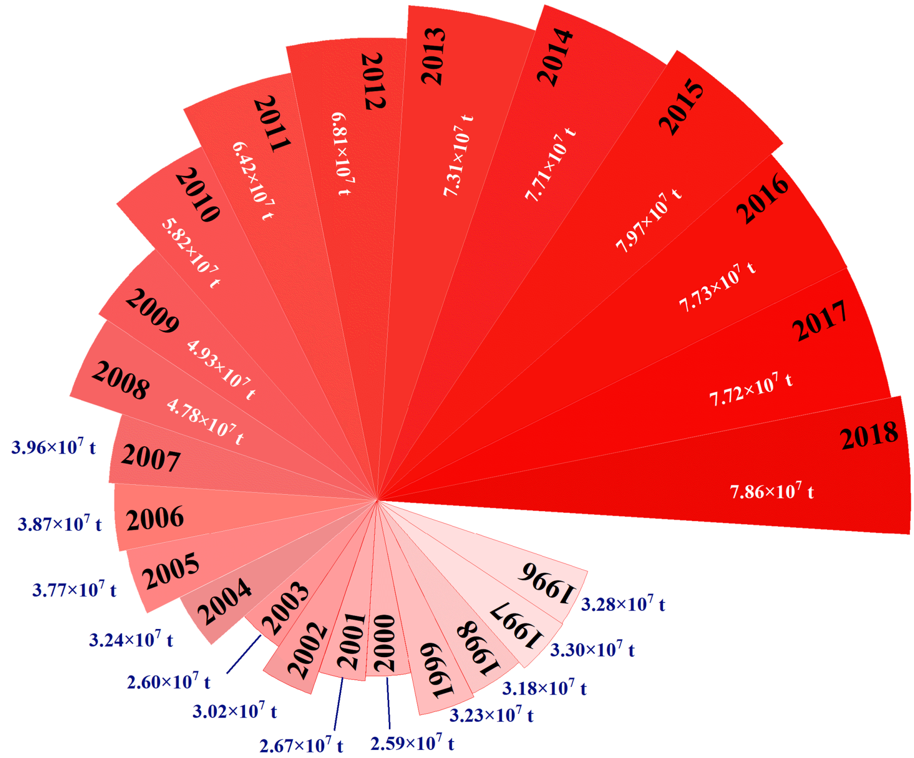

FIGURE 1
The change of available potential crop straws from 1996 to 2018 in Heilongjiang.

highlighting a low education level within the rural labor force in this region. A significant portion of farmers (43.4%) reported a total household income of less than 20,000 yuan, while 37.8% fell within the range of 20,000 to 50,000 yuan. The identified characteristics of the selected samples align with the fundamental features of Chinese farmers, rendering the sample situation representative to a certain extent.

In China's rural areas, a key contradiction exists—more people but less land. The transfer of surplus rural labor has become a focal point of social concern (Shao et al., 2021). As illustrated in Table 2, when household size ranges from four to six persons, the agricultural labor force is predominantly less than 2 persons (83%). In families with over 7 members, the primary agricultural labor force comprises only one to three individuals. Owing to regional economic imbalances, the migration of rural labor to urban areas has resulted in a dearth of young labor in the relatively underdeveloped central and western regions. In recent years, the number of rural migrant workers has increased, with approximately 80% being young and middle-aged laborers. However, there has been a decline in the willingness of rural laborers to develop in rural areas, and the number of transferred laborers returning to rural areas has notably decreased.

### 3.2.2 Current situation of straw disposal and utilization analysis

In China, significant attention has been directed toward the issues of agricultural environment and agricultural resource utilization (Liu et al., 2009, 2021; Li P. et al., 2019). Heilongjiang Province has enacted policies such as the Implementation Plan for Comprehensive Straw Utilization in Heilongjiang Province, which emphasizes the primary methods of straw recycling as straw incorporation into the field, utilization as fuel, and incorporation into livestock feed. Supporting policies primarily involve subsidies for straw incorporation, straw management, and machinery procurement. National-level support policies have played a constructive role in promoting the adoption of crop straw utilization practices within Heilongjiang Province. However, due to an excessive production of straw and limited awareness and acceptance among farmers, the widespread adoption of straw incorporation and comprehensive utilization still faces substantial challenges.

Crop residues, including straw and stubble, primarily serve three main purposes: field incorporation, communal recycling, and open-field burning (as depicted in Figure 3). On an annual basis, during autumn plowing, approximately 30% of straw is reintroduced into fields, thanks to supportive agricultural policies. However, despite the substantial volume of straw generated, various challenges and impediments exist in its collection and utilization, with limited methods for resource utilization. Furthermore, many farmers perceive the cost of straw collection as prohibitive, resulting in low returns (approximately 20%). This process is also time-consuming and labor-intensive (around 41.3%), leading to reduced motivation among farmers (approximately 8.1%). This situation is mainly attributed to the fact that the costs associated with straw harvesting and recycling are higher than those for field incorporation (Sun et al., 2017). Consequently, in order to reduce costs and save time, many farmers opt for open-field straw burning (approximately 33%) and communal straw collection (approximately 35%). During communal straw recycling, surplus crop residues are collectively packaged and managed by local villages. Village authorities often choose to stack and burn

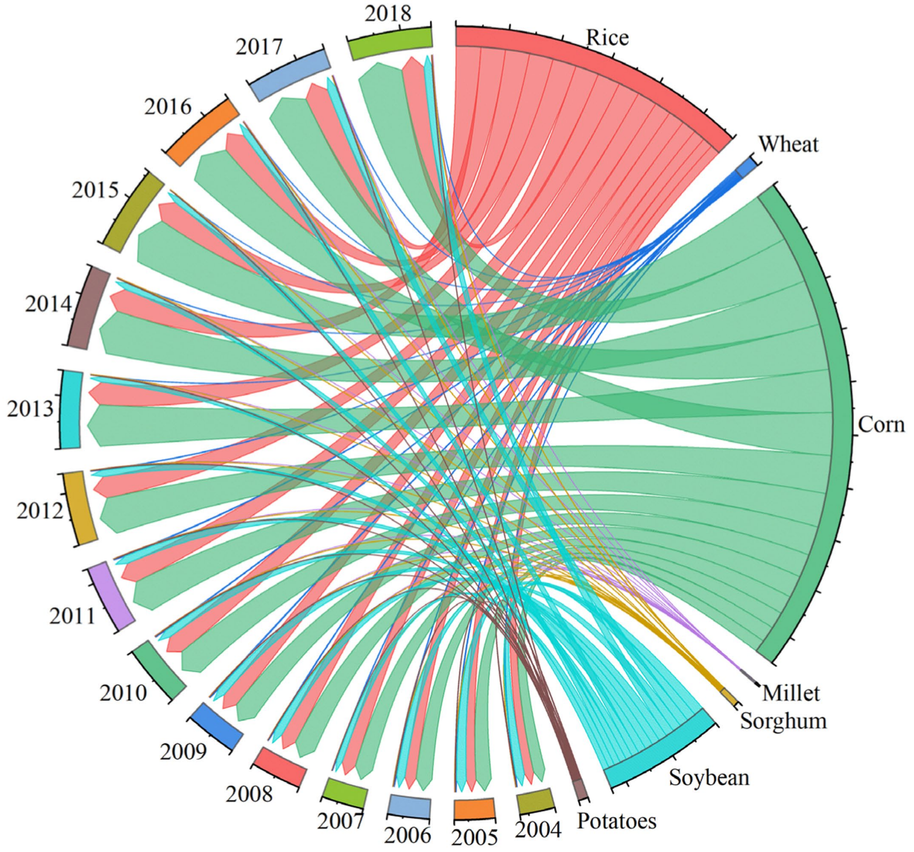

FIGURE 2
The change of available potential various crop straws from 2004 to 2018 in Heilongjiang.

**TABLE 2** Household size and number of labor.

| Agricultural labor family size | <2 people | 2–3 people | >3 people |
|---|---|---|---|
| 1–3 people | 93% | 7% | 0% |
| 4–6 people | 83% | 16% | 1% |
| 7 or more people | 47% | 38% | 15% |

these residues in open areas, accounting for approximately 48.4% of the total (as illustrated in Figure 4). About 32.18% of straw is managed and utilized by companies, while the remainder is typically allocated for livestock feed and other purposes. Since 2015, Heilongjiang Province has fully enforced a policy prohibiting straw burning (Huang et al., 2021). However, due to the aforementioned challenges and conflicts, instances of farmers illicitly appropriating straw resources have been on the rise in recent years. The practice of concentrated open burning during autumn, when straw is damp and available in large quantities, results in significant smog production and contributes to air pollution. In cases of adverse weather conditions, this can further exacerbate the occurrence of seasonal haze (Zhou et al., 2017).

Secondly, the configuration of the land (39.7%), the limited mechanization technology in field incorporation (80%), and the gradual decomposition of straw upon incorporation (32.4%) are factors that adversely affect the efficacy of straw field incorporation. This can be attributed to the low temperatures experienced during the autumn and spring in northern regions, leading to prolonged winter freezing times and hindered decomposition of straw in the fields (Sun et al., 2017). Consequently, the traditional and inefficient comprehensive utilization of straw resources necessitates enhancements in resource utilization technologies. Regarding the remaining straw after field incorporation, 57.5% of farmers prefer corporate buyers to collect them without subsidies, 18.9% hope for communal collection by villages and towns, and 19.3% wish to handle the collection themselves. Addressing the challenge of straw collection is pivotal in mitigating straw field burning and haphazard stacking. Hence, effectively organizing collectors to promptly and efficiently gather straw proves to be an efficacious approach in discouraging farmers from resorting to burning and stacking practices.

## 3.3 Emission inventory and energy potential of straw open burning

The open burning of straw has a significant detrimental impact on the environment. Using the year 2018 as a case study, assuming the worst-case scenario, the primary pollutants released during the open burning of rice, wheat, and corn stalks include $PM_{10}$, $PM_{2.5}$, VOCs, $NO_x$, $SO_2$, CO and $NH_3$. The emissions resulting from this open burning are detailed in Table 3. Notably, among these emissions, the open burning of corn stalks stands out as the largest contributor to

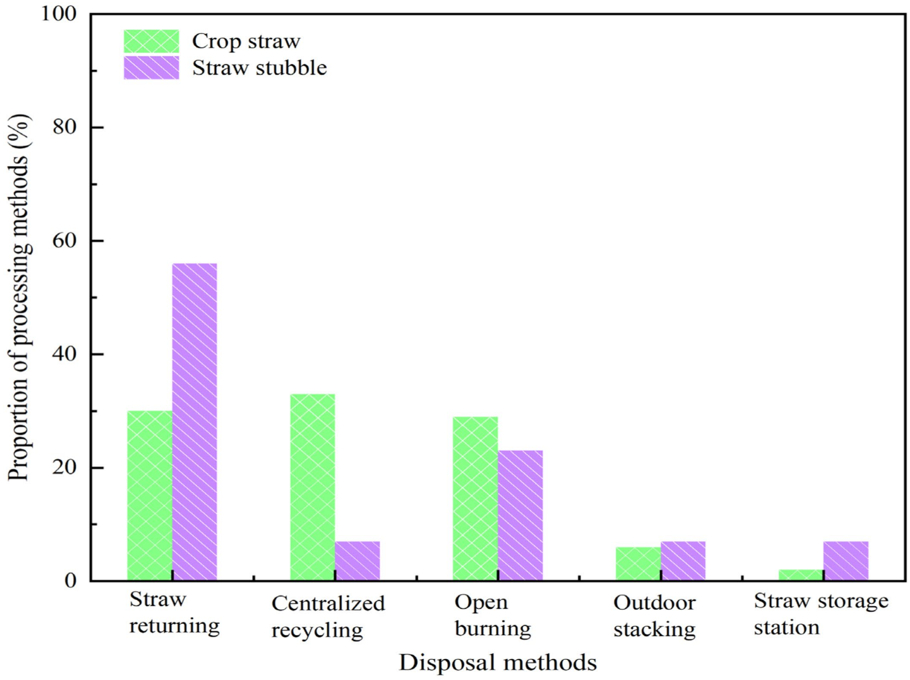

FIGURE 3
Utilization of straw and stubble of farmers in Heilongjiang (Straw is the general term for the stems and leaves of crops after harvesting, while stubble is the rhizosphere left in the soil after harvesting).

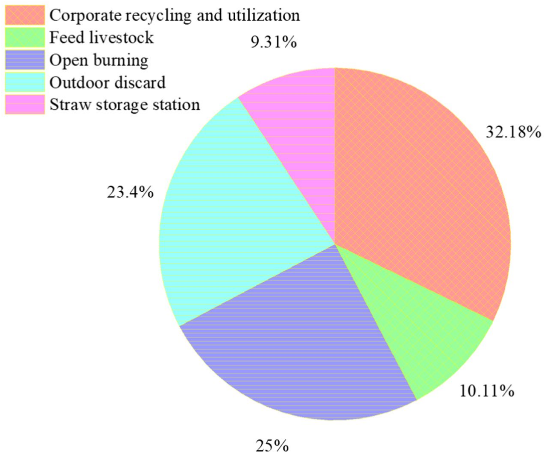

FIGURE 4
Centralized disposal and utilization of crop straw.

pollutant emissions. Additionally, the greenhouse gases produced during this process exert significant pressure on non-point source pollution in agricultural areas. Therefore, there is an urgent need for the effective utilization of corn stalk resources. These resources should be leveraged as a pivotal means of reducing carbon emissions in rural regions of Heilongjiang.

Crop straw represents a promising source of renewable and clean energy, offering significant economic, social, and environmental advantages through its resource utilization. In this study, we explore the potential of converting rice, corn, soybean, and wheat straw from Heilongjiang Province into electricity, which has the capacity to generate a substantial 1.74 billion kilowatt-hours (kWh) of electricity. It is worth noting that most thermal power plants typically achieve a direct combustion efficiency of 50%, resulting in the production of 870 million kWh of electricity. By employing a standard coal consumption calculation of 0.31 tons per kWh of electricity generated, the utilization of straw for power generation can effectively reduce the consumption of approximately 2.7 million tons of standard coal. The corresponding reductions in emissions of various air pollutants, including $PM_{10}$, $PM_{2.5}$, VOCs, $NO_x$, $SO_2$, CO and $NH_3$, are detailed in Supplementary Table S3. The potential replacement of fossil fuels with straw power generation holds the promise of not only mitigating the pressure stemming from the depletion of fossil resources but also addressing the environmental challenges associated with straw waste. This transition carries substantial significance in the pursuit of establishing a clean energy environment and achieving carbon reduction goals.

## 3.4 Farmers' willingness for straw disposal and utilization

### 3.4.1 Structural equation model construction

The equations were subjected to testing using AMOS (Analysis of Moment Structure) 22 on the model's variables, with the addition of covariance and causality analysis between the error terms and measured variables. This approach is widely employed in refining Structural Equation Models (SEM) and enhancing model fitting. As depicted in Figure 5A, the CMIN/DOF ratio stands at 3.419, indicating a less-than-optimal degree of fit. Additionally, the PGFI (0.514) exceeds the 0.5 threshold, and RFI is equal to 0.79, both of which fail to meet the established standards.

TABLE 3 Emission inventory of crop residues open burning.

| Crops | $PM_{10}$ | $PM_{2.5}$ | VOCs | $NH_3$ | $NO_X$ | $SO_2$ | $CH_4$ | CO | $CO_2$ |
|---|---|---|---|---|---|---|---|---|---|
| Rice (×$10^4$ t) | 29.4 | 66.2 | 31.1 | 4.1 | 15.8 | 4.6 | 16.3 | 152.8 | 7435.7 |
| Wheat (×$10^4$ t) | 1.6 | 1 | 1 | 0.1 | 0.4 | 0.1 | 0.5 | 8.4 | 191.3 |
| Corn (×$10^4$ t) | 42.1 | 63.8 | 56.7 | 3.8 | 23.4 | 2.2 | 24.5 | 294.3 | 7357.5 |
| Soybean (×$10^4$ t) | 13.2 | 6.3 | 16.5 | 1 | 2.1 | 0.6 | 7.4 | 63.7 | 2745.5 |

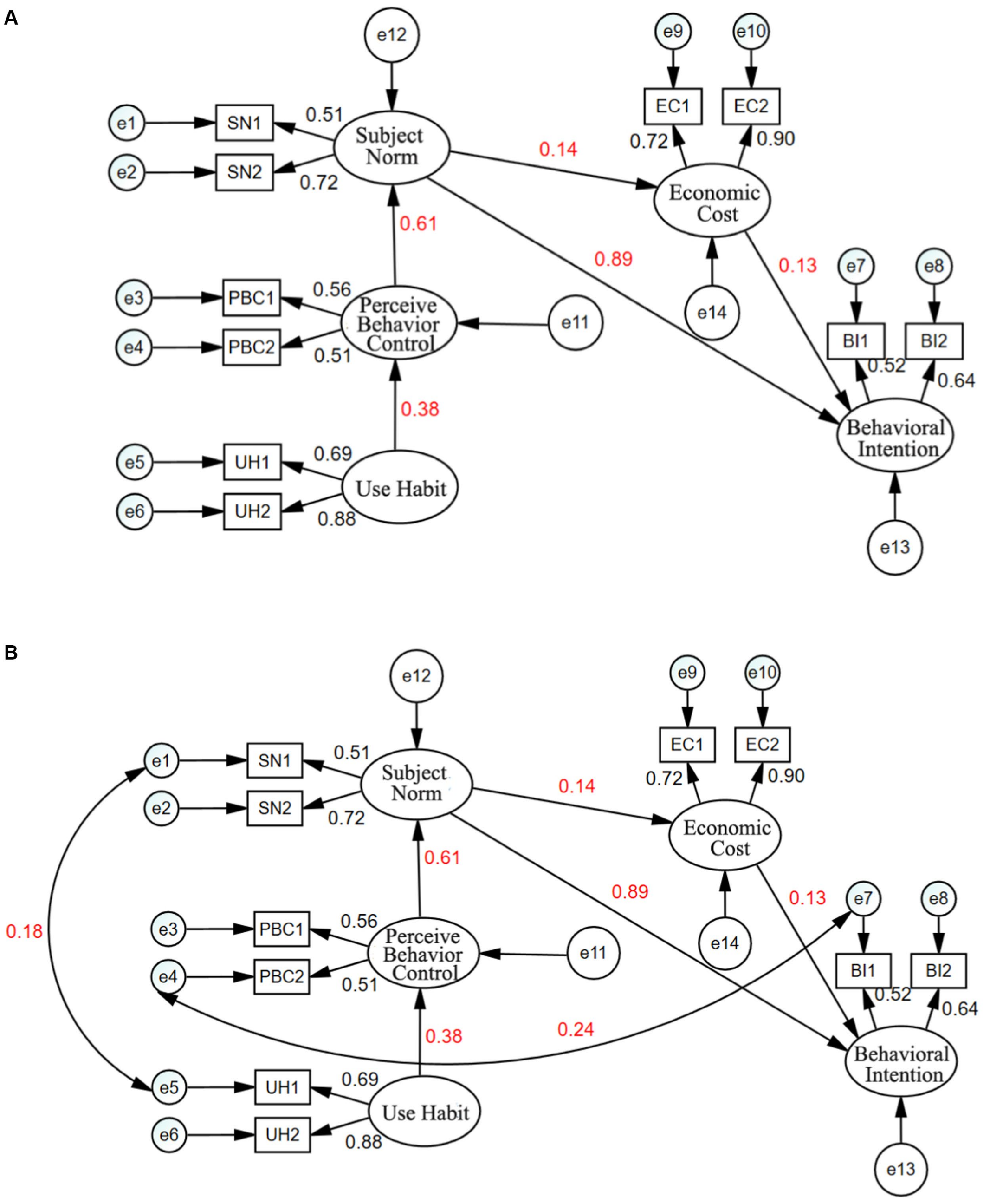

FIGURE 5
The SEM model before **(A)** and after **(B)** modification based on TPB theory framework. Note: The ellipse is the latent variable; the rectangle is the measurement variable; the circle is the residual; the arrow is the path; the value is the path coefficient.

Following the model guidelines, we iteratively applied path corrections and re-ran the model. The test results for each fitness indicator of the revised model are presented in Tables 4, 5. All indicators exhibited ideal values, signifying a robust overall fit between the model and the sample data (Hussain et al., 2018). Construct validity tests relied on factor loading values and mean variances. The

TABLE 4 The results of model hypothesis test and imitative effect.

| Fit index | Value | Judgment value | Fitting results |
|---|---|---|---|
| CMIN/DF | 2.885 | <3 | Acceptable |
| GFI | 0.954 | >0.9 | Ideal |
| AGFI | 0.910 | >0.9 | Ideal |
| NFI | 0.900 | >0.9 | Ideal |
| IFI | 0.925 | >0.9 | Ideal |
| PGFI | 0.486 | <0.5 | Ideal |
| CFI | 0.923 | >0.9 | Ideal |
| CN | 500 | >200 | Ideal |

TABLE 5 The meaning statistic of variables and factor load value.

| Latent variable | Observed variable | | Factor loading values |
|---|---|---|---|
| Use habit, UH | UH1 | Awareness habit of burning straw in open field | 0.68 |
| | UH2 | Farmers' habit of discarding straw | 0.88 |
| Economic cost, EC | EC1 | Expected subsidies for farmers to dispose of straw | 0.72 |
| | EC2 | Hope the straw is handled for free, no subsidy required | 0.90 |
| Subject norm, SN | SN1 | Policy to ban farmers from burning straw | 0.72 |
| | SN2 | Time to implement straw burning ban | 0.51 |
| Perceive behavior control, PBC | PBC1 | Awareness of stacking or burning straw can reduce carbon | 0.55 |
| | PBC2 | Awareness of straw recycling and utilization | 0.51 |
| Behavioral intention, BI | BI1 | Farmers' willingness to reduce carbon emissions | 0.52 |
| | BI2 | Farmers' willingness to input and output | 0.64 |

mean variance represents the average variance of the indicators loaded onto the extracted structure, with a value of 0.53 (>0.50), indicating satisfactory convergence (Qureshi and Kang, 2015; Duff, 2019). Furthermore, the factor loading values exceeded 0.50, indicating an acceptable level of construct validity. Ultimately, the improved model with a better fit is displayed in Figure 5B.

### 3.4.2 Farmers' behavioral willingness

Drawing upon the theoretical framework of the Theory of Planned Behavior (TPB), we developed a Structural Equation Model (SEM) to examine the carbon emission reduction behavior of farmers. Our analysis revealed a significant relationship between latent variables (Table 5) and observable variables, suggesting a strong interplay among four latent variables: farmers' behavioral habits, subjective norms, perceived behavior, and economic costs. These latent variables, either directly or indirectly, exert influence on farmers' carbon emission reduction behavior.

Notably, we found a substantial and positive correlation between utilization habits and perceived behavior ($p < 0.01$, $R = 0.38$), providing support for our H1 hypothesis, which posited that farmers' recycling and utilization habits are positively associated with their perceived control over behavior. The habitual experiences of farmers have a lasting impact on their subsequent behaviors. Furthermore, the pleasantness of their recycling experiences shapes their perceptual awareness, subsequently influencing their behavioral choices. In essence, farmers who exhibit stronger habits of straw disposal and utilization tend to have heightened awareness of environmental conservation principles. Specifically, the load values for UH1 (awareness of habit regarding burning straw in open fields) and UH2 (farmers' habit of discarding straw) were 0.685 and 0.881, respectively, both exceeding the threshold of 0.6. These values indicate that farmers' practices of either stacking or burning straw in their fields have a substantial impact on the environment and straw utilization, directly influencing farmers' perception-based behavior. These findings underscore the significance of farmers' habits in either stacking or burning straw in the field, highlighting their pivotal role in shaping awareness and behaviors related to carbon emission reduction.

The study revealed a significant positive correlation between farmers' perceived behavior and subjective norm ($r = 0.612$, $p < 0.01$), thereby providing support for Hypothesis 2 (which posited that subjective norm would exhibit a positive correlation with perceived control). This suggests that enhancing farmers' awareness of environmental pollution and promoting straw recycling can positively influence subjective norms, leading to improved cooperation among farmers in the carbon emission reduction process. Additionally, both observed variables, PBC1 (awareness of the carbon-reduction potential of not burning straw) and PBC2 (awareness of straw recycling and utilization), displayed load values exceeding 0.5, indicating their substantial contributions to farmers' perceptions of carbon emission reduction.

Furthermore, the study found a significant positive correlation between subjective norm and behavioral intention ($p < 0.01$, $R = 0.89$), lending support to Hypothesis 3 (which posited a positive correlation between subjective norm and behavioral intention). Additionally, economic cost exhibited a significant positive correlation with behavioral intention ($p < 0.01$, $R = 0.13$), confirming Hypothesis 4 (which suggested a positive correlation between subjective norm and economic cost). Notably, the results emphasize that subjective norm exerts a more substantial influence on behavioral intention than economic cost. Therefore, strengthening the influence of subjective normative factors among farmers is more effective than solely focusing on controlling economic costs, although economic considerations remain essential. In particular, subjective norm factors such as SN1 (policy to ban farmers from burning straw) and SN2 (timeframe for implementing the straw burning ban) reflect the popularity and timing of straw burning ban policies, significantly impacting farmers' willingness to engage in straw-related activities, highlighting the dominant role of local governments in rural policy implementation.

Economic cost exhibited a significant positive correlation with behavioral intention ($p < 0.01$, $R = 0.89$), thus providing support for Hypothesis 5, which posited a positive relationship between economic cost and behavioral intention. In examining the components of economic cost, it was observed that the load coefficients for EC1 (expected subsidies for farmers to dispose of straw) and EC2 (expectation of straw being handled for free, without the need for subsidies) were 0.52 and 0.81, respectively. These coefficients suggest that the process of self-handling straw is both time-consuming and financially burdensome for farmers, rendering it impractical for them to manage independently. This impracticality, in turn, has a detrimental impact on farmers' willingness to utilize straw resources. Hence, it becomes paramount to enhance the efficiency of straw collection, storage, and transportation processes. To address this issue effectively, it is advisable to adopt an approach that considers the specific circumstances of each locality. Integrating various processing technologies and methods tailored to the local context can prove instrumental in resolving the challenges associated with straw recycling.

# 4 Discussion and recommendations

## 4.1 Improving straw disposal

Traditional crop straws have historically been primarily utilized for heating and cooking purposes, with instances of field burning and stacking being relatively uncommon. Farmers have traditionally held the belief that burning and stacking have negligible contributions to carbon emissions. However, in recent years, the widespread adoption of electrified heating and liquefied gas cooking methods (Zhang and Li, 2022) has led to an excess of crop straw in rural areas, necessitating a shift in traditional straw disposal practices. Farmers themselves must modify their customary habits of straw stacking and burning to facilitate the comprehensive utilization of straw and, consequently, reduce carbon emissions. Research indicates that the transformation in straw disposal habits primarily stems from the influence of peers, village leaders, and guidance provided by agricultural experts. Heightened environmental awareness has enlightened farmers about the advantages of proper straw disposal and utilization. Therefore, in the pursuit of reducing agricultural carbon emissions, it is imperative to recognize the influential role of village leaders and farmers' advocates. They represent the driving force behind cultivating a positive awareness among farmers regarding carbon emission reduction practices.

## 4.2 Improving farmers' willingness

Farmers' awareness of carbon emission reduction and straw utilization significantly influences subjective norms within agricultural communities. Consequently, government policies related to straw management must be tailored to local circumstances and aligned with farmers' actual practices. As farmers' environmental consciousness and understanding of straw recycling improve, their attitudes and behaviors toward these practices strengthen. This heightened awareness enhances the feasibility of comprehensive straw utilization policies and carbon emission reduction initiatives. Strict adherence to subjective norms amplifies farmers' willingness to responsibly dispose of and utilize straw resources. Therefore, well-designed policies play a pivotal role in shaping the landscape of straw utilization and carbon emission reduction efforts in Heilongjiang Province. Following policy implementation, it is crucial to conduct follow-up assessments and refine the policies based on public feedback. This iterative process ensures policy alignment with local realities, fostering correct straw disposal and utilization practices among farmers. Research findings indicate that shifts in straw disposal habits primarily stem from the influence of friends, village leaders, and agricultural experts. In the realm of agricultural carbon emission reduction, it is vital to recognize the influential role of village leaders and farmer advocates. These individuals serve as catalysts, driving farmers to adopt positive attitudes and behaviors related to carbon emission reduction. Therefore, special attention should be given to empowering village cadres and farmers' advocates, recognizing them as the main drivers behind the cultivation of a strong carbon emission reduction awareness among farmers.

## 4.3 Suggestions

The government should devise pertinent policies concerning straw utilization and carbon emission reduction, taking into consideration the willingness of farmers to engage in such practices. A comprehensive analysis reveals that converting all open-air straw burning into electricity can yield significant economic benefits. Simultaneously, this approach effectively addresses the environmental pollution associated with straw burning, thereby promoting carbon emission reduction in rural areas and enhancing the overall quality of the rural environment. Given the unique characteristics of each region, it is imperative for local governments to enhance the processes involved in harvesting, storing, and transporting straw. These improvements constitute a critical strategy for advancing carbon emission reduction initiatives in rural areas. To bolster farmers' fundamental understanding of these practices, government policies should prioritize user-friendly straw recycling technologies. Region-specific agricultural machinery designed for straw resource utilization and convenient recycling techniques should be developed and disseminated widely. This will serve to reduce the time and economic burden on farmers, encouraging active participation in straw recycling and rural carbon emission reduction efforts. Moreover, harnessing the leadership and guidance of village cadres and exemplary farmers is crucial. These community leaders and role models should be mobilized to guide farmers in strengthening their awareness of straw utilization and carbon emission reduction. By demonstrating the tangible benefits of straw recycling, these influencers can inspire farmers to embrace these practices more enthusiastically.

## 5 Conclusion

The effective utilization of straw plays a critical role in carbon emission reduction and achieving carbon peaking. As the key participants in rural carbon emission reduction, farmers' willingness and behaviors should be fully respected. This study analyzed the farmers' willingness to reduce carbon emissions in Heilongjiang Province through SEM structural equation modeling, based on the investigation of crop straw production and utilization status. The findings indicate that maize and rice are the main sources of straw in Heilongjiang Province. Farmers generally perceive the current straw collection process as expensive, time-consuming, and labor-intensive, leading to low enthusiasm for straw recycling. Although returning straw to the field is the mainstream disposal method guided by policies, its effectiveness has been less than satisfactory. Traditional habits among local farmers still contribute to the persistence of straw burning and stacking. The main pollutants generated from open burning of straw are $PM_{10}$, $PM_{2.5}$, and $CO_2$, with corn straw combustion being the primary contributor to rural carbon emissions. Furthermore, farmers' habits of straw stacking or burning directly impact their awareness of straw utilization and carbon emission reduction. The lack of proper guidance on traditional straw disposal habits among farmers, along with subjective norms, significantly influence their awareness of carbon emission reduction. Additionally, farmers' awareness of carbon emission reduction correlates positively with perceived behavior. The extent of farmers' understanding and implementation of relevant policies has a significant impact on their willingness to engage in behavior change. Factors such as high disposal costs, difficulty in collection, and the time and effort required are major reasons why many farmers exhibit negative attitudes toward straw recycling. In conclusion, the behavioral willingness and perceived behavior of farmers have a crucial impact on the process of straw recycling and rural carbon emission reduction. Thus, policy formulation processes should fully consider farmers' willingness and local conditions.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

JH: Funding acquisition, Writing – original draft, Project administration. CY: Conceptualization, Data curation, Investigation, Software, Writing – review & editing. HL: Data curation, Formal analysis, Methodology, Writing – review & editing. MY: Formal analysis, Validation, Visualization, Writing – review & editing. AC: Formal analysis, Writing – review & editing. YX: Formal analysis, Writing – review & editing. ZM: Formal analysis, Writing – review & editing. GC: Writing – review & editing. JZ: Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing, Writing – original draft.

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## Conflict of interest

HL was employed by CCEED Eighth Bureau Decoration Engineering Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note

## Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1288763/full#supplementary-material

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