

## Research Article

# Comparative Environmental Evaluation of Straw Resources by LCA in China

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Crop straw, as a widely used biomass resource, can be processed to produce renewable energy and green products. However, about 70% of straw were burned in the open air, causing serious environmental pollution and air pollution. In order to reduce the burden on the environment, the different straw management strategies are comparatively studied and evaluated by applying the life-cycle assessment (LCA) method. Within the system boundary from cradle to grave, three alternative scenarios, including straw particleboard, straw cement-bonded particleboard, and straw direct combustion power generation, are compared with the current common treatment (straw open burning). The comprehensive inventory analysis on each treatment scenario is carried out in-depth, and the corresponding resource consumption and environmental impact of each treatment scenario are calculated, respectively. The LCA results showed that the environmental impacts of reusing crop straw to produce straw particleboard and cement-bonded particleboard (Scenario 1 and Scenario 2) is significantly reduced by 6% and 10%, by comparison with the use of wood resource. Greenhouse gas emissions from straw direct combustion power generation (Scenario 3) processes are reduced by 30% compared with coal power generation. From the environmental point of view, the scenario of straw particleboard product has the smallest impact on the environment, while straw open burning is not an advisable way due to the highest environmental impact from the highest greenhouse gas emissions and acidification effects. From the perspective of energy consumption, the energy consumption for the combustion power generation is the smallest in all scenarios. It is suggested that governments are supposed to construct reasonable scenarios for the straw disposition based on the local development status and condition. The research results can provide scientific guidance for the management strategy of the comprehensive utilization of straw resources.

## 1. Introduction

About 1 billion tons of crop straw was generated each year in China and brought a severe burden to cities and natural environment. Recycling and reusing crop straw is a practice pathway to dispose the agricultural waste. Comprehensive utilization of straw resources can not only improve agricultural efficiency but also save resources and protect the ecological environment [1, 2]. It is reported that recycled crop straw can be used to produce particleboard, cementitious composite board, and other building materials [3–5], and beyond that, crop straw can also be used for energy conversion for direct-fired power generation [6–8]. These reuse schemes can make full use of excess straw resources and alleviate environmental pressure. Several studies have

shown that it is technically feasible to utilize the straw for fiberboard production [9, 10]. Crop straw can replace wood materials to produce fiberboard with different densities (low, medium, and high densities), which has good mechanical properties and saves forest resources [11]. The cement composite board prepared by using straw as the reinforcing material has low cost, acceptable strength, and good waterproofing performance [12–14]. Furthermore, the characteristics that less sulfur and ash content than coal make inflammable crop straw to be a good fuel resource. Some biomass power generation has been developed by replacing fossil fuels with straw or other agriculture wastes [15–17]. In the case of various possibilities of reuse, it is of significance to adopt scientific and reasonable methods to develop and manage the straw.

Life-cycle assessment (LCA) is a tool for green products to assess the environmental impact throughout their life cycle that can effectively recognize and quantify the resource consumption and environmental impact of products [18–20]. Several LCA studies on biomass conversion have been published, such as direct biomass combustion for power generation in China, France, and the US [21–24]. Besides, the use of LCA has been mainly applied on energy conversion strategies, such as power generation, biogas, and agriculture. LCA can help compare potential factors and environmental impact types in different stages. Medium-density fiberboard was assessed based on LCA during the production process [25, 26]. Umberto software and Ecoinvent life-cycle inventory database were used to establish different life-cycle models of fiberboard manufacturing [27–29]. Some applications of LCA in power generation were carried out as a life-cycle assessment of straw power generation in Spain. It is found that greenhouse gas emissions in power station reduced and met the EU's 60% sustainability standard when natural gas is replaced by straw [17]. Moreover, it has saved 1.7 kg CO<sub>2</sub> eq/kWh of greenhouse gas emissions when compared with the traditional power generation method [30]. In the application of LCA, multiple schemes and even multifield comparisons can be performed. Not only can it be combined with other methods, such as Technology for Order Preference by Similarity to an Ideal Solution, TOPSIS, for multiobjective decision-making but also sensitivity analysis can be conducted to explore the impact of certain factors on the environment [1, 31]. LCA is conducted for environmental problems of different straw utilization systems, such as direct combustion power generation, biomass conversion to ethanol or biogas, and thermochemical conversion to biodiesel and fertilizer as soil [32]. It is possible to establish a life-cycle assessment model of medium-density fiberboard, bioethanol, combined heat power, and corrugated base paper to compare pollutant emissions from different options and direct incineration [33]. In agriculture, the reuse of straw brings great environmental benefits and avoids the environmental impact of incineration [34, 35]. The life-cycle assessment of the boards and power generation made from waste wood is compared with the traditional landfill treatment. The waste of abandoned materials such as wood can be effectively avoided [36–38].

Overall, scholars have carried out some aspects of LCA research on the reuse of straw, but single resource reuse in these methods or systematical evaluation in the frame of a single form of treatment were always dealt with. There is a lack of multiway comparative study on multiaspect utilization of straw resources, and most of the existing results are only for the impact of the greenhouse effect on the environment, but resource consumption also needs consideration. In this study, a comparative environmental evaluation of straw resources was conducted by LCA based on the data from China. The objectives of the study are to (i) select four typical treatment schemes, including straw particleboard production, straw cement-bonded particleboard production, straw direct combustion power generation, and straw open burning (common management method in China), (ii) evaluate and

compare the environmental impacts and energy consumption of the four scenarios, and also (iii) compare these disposal scenarios with the traditional disposal methods of raw materials or fuels. It provides a theoretical basis for improving the environmental quality issues caused by improper straw treatment and promoting the sustainable development of straw resource utilization.

## 2. Methodology

*2.1. Study Method.* For the sake of providing a reasonable scientific basis for straw management, this study adopted a common method of environmental impact assessment, namely, life-cycle assessment (LCA). According to ISO, LCA research includes four main steps: (1) the determination of research objectives and scope, including system boundaries, functional units, and the determination of evaluation objectives; (2) life-cycle inventory (LCI) analysis and, according to determination of objectives and scope, processing data such as material and energy consumption in all stages of life cycle; (3) impact evaluation and quantitative evaluation of the impact of the inventory; (4) explanation of the results and providing the results for interpretation and analysis. The LCA technical framework is shown in Figure 1.

Since life-cycle assessment studies inevitably require the collection and processing of data sets for different production processes, the results of the evaluation may be affected by different kinds of factors and conditions. In the life-cycle assessment of products, various factors have different effects on the results. At this time, it is necessary to conduct sensitivity analysis. In the evaluation process, other external conditions, such as data collection, data sources, and material transportation distance, have affected the outcome. Therefore, a sensitivity analysis of the greenhouse gas emissions of the studied management systems is conducted to assess uncertainties associated with transport distances, power consumption, and so on. Oracle Crystal Ball is a Monte Carlo simulation software, also known as Monte Carlo Crystal Ball software [39]. The main functions of the software are predictive modeling, prediction, simulation and optimization, random simulation, and uncertainty risk analysis, which can insight into the key factors affecting risk. In Section 3.5, by using the Oracle Crystal Ball software, the key parameters are simulated for 1 million times in the range of  $\pm 20\%$ , and the contribution rate of the key parameters to the environmental performance of different scenarios systems was obtained.

*2.2. Objectives and Scope of the Study.* Different straw management scenarios are selected, and the environmental impacts of assessment and comparison scenarios are taken as the research objectives. Three typical resource utilization scenarios are selected and compared with the reference scenario (open burning), and the functional unit of comparison between scenarios is 1 ton of straw. Agricultural production activities such as crop cultivation, farming, and fertilization are not considered in this analysis.

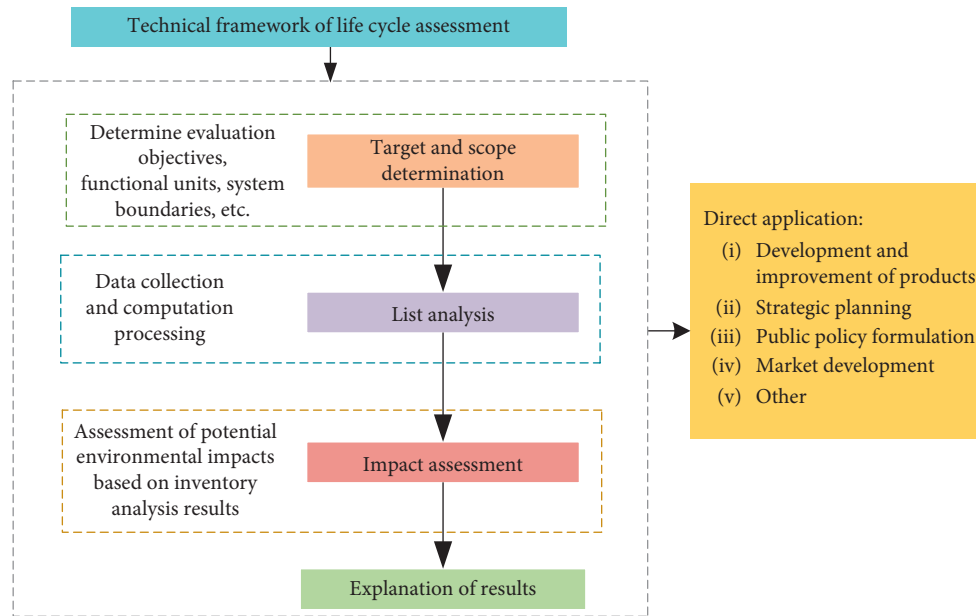


FIGURE 1: Technical framework for life-cycle assessment.

The specific treatment scenarios of waste straw are as follows:

Scenario 1. Particleboard is produced with waste straw (particleboard plant is located in Jilin province, China).

Scenario 2. The cement is used as the base material and straw fiber as reinforcing material to make straw cement-bonded particleboard (the plant is located in Jilin province, China).

Scenario 3. Direct combustion of straw is done for power generation (the power plant is located in Jilin province, China).

Scenario 4. Straw is open burnt (reference scenario).

**2.3. Scenario Description, System Boundary Determination, and Inventory Analysis.** The detailed process of each scenario is described in the following four subsections, in which different influencing factors are considered. The system boundaries are different for different scenarios, as shown in Figure 2, taking into account cradle to grave system boundaries.

**2.3.1. Statement of Scenario 1.** Straw is processed from the site by a 30-ton truck and transported to the local treatment site. The main mode of transportation is the highway, and diesel fuel is used. Assuming that 1.25 t of straw is needed to produce 1 m<sup>3</sup> straw particleboard and 1.5 t of wood can produce 1 m<sup>3</sup> wood particleboard. Assuming that the loss rate of straw is 1%, 1.26 t straw is transported to the factory to produce 1 m<sup>3</sup> straw particleboard and 1.51 t wood to produce 1 m<sup>3</sup> wood particleboard. The transportation distance is 40 km, and the fuel consumption is 0.06 L/(km·t). The density of diesel oil is usually calculated as 0.85 kg/L. The fuel consumption of freight trucks is 2.5757 kg and 3.0908 kg, respectively [40].

The natural air-dried straw is stored in the drying facility and treated on-site by using a forklift truck. The collected

crop straws are cut into grass sections having a length of 20–40 mm, and the moisture content of the straw is 12–20% [41]. Stone and gravel are removed by air separation and then the moisture content of the raw materials is controlled after 12–8% drying by using a pipeline air-dryer. The abovementioned straw segments are crushed by using a double-axle hammer mill with a screen mesh aperture of 5–10 mm. The crushed fibers are screened into coarse and fine materials by using a wind screener. The moisture content of coarse materials and fine materials is controlled to be 8–14% and 10–14%, respectively. The crude material is used as the core material, and the fine material is used as the surface material, which is sent to the storage silo for uniform mixing (adding MDI). The flame retardant additive and functional additive are added in the mixing process. The mixed material is laid into a slab through a paving machine, and after prepressing, it is subjected to a temperature of 190°C for 70 seconds, and the pressure is 5 MPa. The straw composite board can be obtained by later processing, including sawing and sanding. In the sanding process, it is necessary to remove the release layer to improve the surface quality and decorative performance of the strawboard. After the particleboard has been treated and cooled, it is stored in a place where temperature and humidity are appropriate.

Compared with the production process of wood board, the steps of the peeling machine, the peeling machine of logs, and the peeling-making of wood are omitted so that the energy consumption of these steps is saved. Among them, drying and hot pressing are the main energy use processes, while the fiber preparation, sorting, sizing, paving, preloading, cooling, trimming, sanding, and other processes consume little energy. The life cycles of 1 m<sup>3</sup> straw particleboard and 1 m<sup>3</sup> wood particleboard are compared, and the functional unit is 1 m<sup>3</sup>. Data of materials and energy consumption in transportation and production of particleboard are shown in Table 1. And the composition of straw

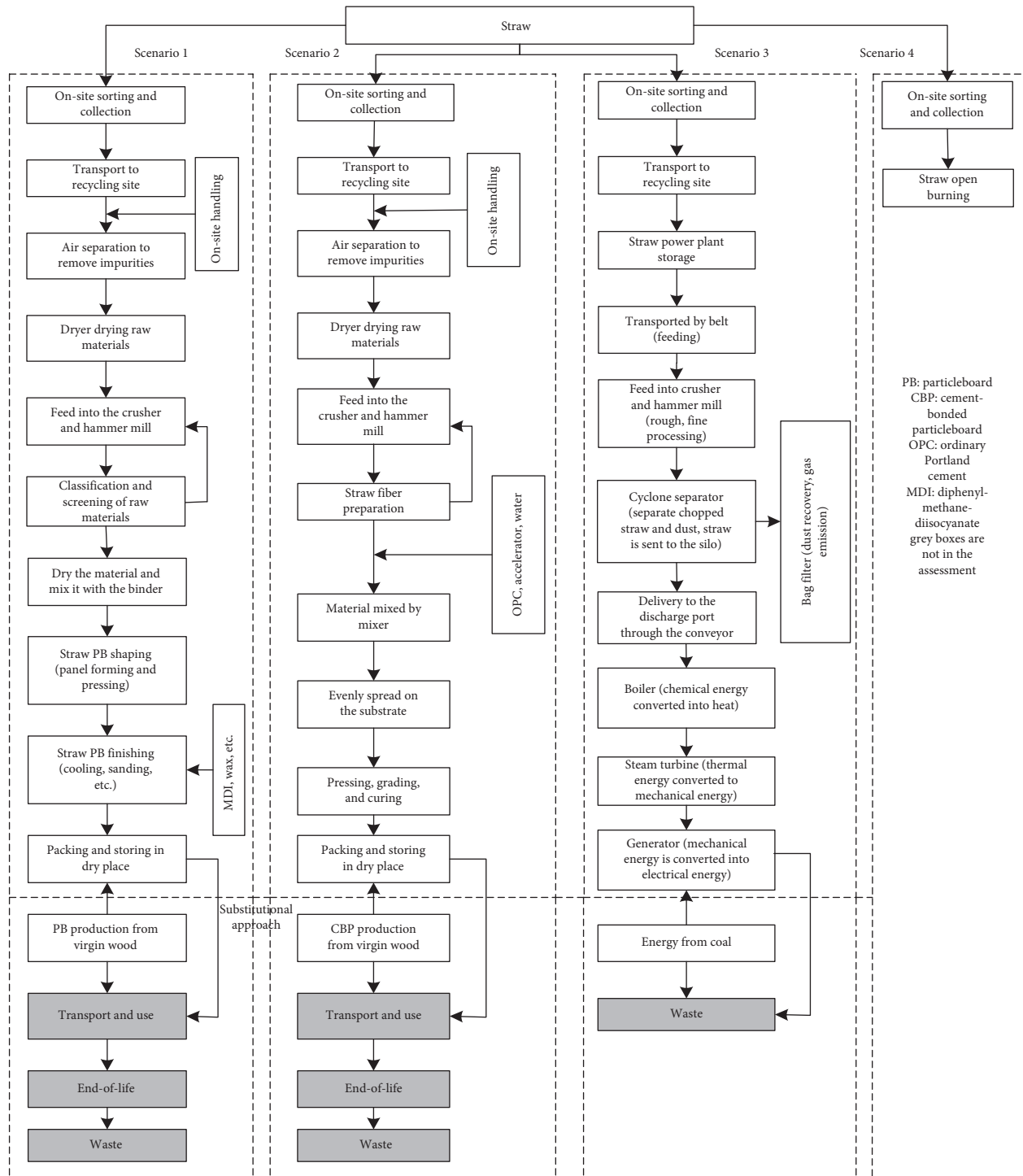


FIGURE 2: System boundary of straw resource utilization under different scenarios.

particleboard is shown in Table 2. The major equipment and energy used in the production process of Scenario 2 are shown in Table 3.

2.3.2. *Statement of Scenario 2.* Straw cement-bonded particleboard has good mechanical properties, mainly using straw fiber as reinforcing material and cement as cementing material, adopting a similar principle to cement particleboard.

The collected straw is cut into straw segments with a growth of less than 50 mm by using a cutting machine, processing into fibers by using a hammer shredder, and it is then sent to an air separator for air separation. The mixed stones are separated, and the wax in the straw is removed by referring to the traditional paper-making technology to make straw fibers. It is mixed with OPC and water, a few catalysts (about 4% of cement weight) into the wet mixture to accelerate the setting of the cement, and

TABLE 1: LCI data for production of 1 m<sup>3</sup> straw particleboard and wood particleboard.

Process of production	Energy consumption	Data sources
Straw particleboard production		
Straw collection and processing	40 km by 30 t trucks	[42, 43]
Straw transport to particleboard production site	Diesel: 2.5757 kg	
Straw processing (preparation of straw, e.g., chips, planing, and screening)	Electricity: 27.3 kWh	[42, 44]
Straw drying	Electricity: 20.4 kWh	
Other materials		
MDI, coatings, solid adhesives, production, and transportation	200 km by 30 t trucks	[42–45]
	Diesel: 0.34 kg	
Production processing (e.g., sheet paving, hot pressing, and cooling trimming)	Raw coal: 16.64 kg	[44]
	Crude oil: 25.14 kg	
Product completion and processing	Electricity: 50.3 kWh	[42–44]
	Electricity: 34 kWh	
Wood particleboard production		
Wood handling and transportation	40 km by 30 t trucks	[42, 43]
Wood transport to particleboard production site	Diesel: 3.0908 kg	[42, 44, 46]
Wood treatment (processing and preparation of wood, e.g., chips, planing, and peeling)	Electricity: 38.7 kWh	
Wood drying		
Other materials		
MDI, coatings, and solid adhesives, production, and transportation	Electricity: 33.8 kWh	[42–44]
	200 km by 30 t trucks	
Production processing (such as sheet paving, hot pressing, and cooling trimming)	Diesel: 0.29 kg	[44]
	Raw coal: 13.961 kg	
Product completion and processing	Crude oil: 22.043 kg	[42, 43]
	Electricity: 48.2 kWh	
	Electricity: 31.2 kWh	
	Diesel: 1.1135 kg	

TABLE 2: Composition of straw particleboard production and the process involved.

Materials	Proportion (%)	Raw materials involved in the process
Straw	97.58	Straw transport to site, straw drying, and straw processing
MDI	1.95	MDI production and transportation
Waterproof agent	0.396	Waterproof agent production and transportation
Mold dope	0.074	Mold dope production and transportation
Finished particleboard (1 m <sup>3</sup> )	100	Board production processing, finishing process, and on-site handling

then it is fed into the air paver through the conveyor. After the mixture is paved by an air-flow paver, the cement straw cement-bonded particleboard is formed, which is stacked neatly by the manipulator on the bottom module of the clamping device. After stacking several pieces, the pressure module is pressed up. After being fed by the rolling table, the pressure is reached, and then the mold is pressed. Finally, it is sent to the drying room for heating and maintenance through the rolling table. After 6 hours of maintenance, it is sent to the unloading section. Mold unloading is completed and transferred by using a forklift to the stacking site for natural maintenance. Ultimately, after 30 days of sawing, sanding, warehousing, and storage, the final strength reached 95% and the slab can be released from the factory. Therefore, the water content of the final products is about 7.5–10%, the optimum density of straw cement-bonded particleboard is about 1370 kg/m<sup>3</sup>, and the bending strength of 28 days is 11.8 MPa, in line with ISO standards [47]. Data of materials and energy consumption in transportation and production of cement particleboard are shown in Table 4. And the composition

of straw cement-bonded particleboard produced is shown in Table 5.

The pollutant data of electricity production in Table 6 are calculated based on the average energy consumption of China's power generation of 0.424 kg standard coal/kWh, which is equivalent to the calorific value of 4244 kJ/kg of coal. The ash content is calculated as 20%; and the NO<sub>2</sub> and SO<sub>2</sub> production in the power generation and transportation systems are calculated based on the corresponding average emission factors. All raw materials are mined with the same electricity consumption, without considering other pollutants. According to the data in Table 6, the corresponding environmental results can be calculated. The main equipment used in the production process of Scenario 1 and its energy consumption are shown in Table 3.

2.3.3. *Statement of Scenario 3.* Straw direct combustion power generation is a power generation method using crop straw as the main fuel. Moreover, the average sulfur content of straw is only 3.8 parts per thousand, which can replace

TABLE 3: Major equipment and energy used in the production process of Scenarios 1, 2, and 3.

Equipment	Function	Energy
Crusher, hammer mill (Scenarios 1, 2, 3)	Preparation of fibers	Electrical energy
Dryer (Scenarios 1, 2, 3)	Fiber drying	Electrical energy, thermal energy
Sizing system (Scenarios 1, 2)	Sizing, waterproofing agent	Electrical energy
Blender (Scenario 2)	Mixing fiber and cement	Electrical energy
Paving machine (Scenarios 1, 2)	Fiber pavement forming	Electrical energy
Hot press (Scenarios 1, 2)	Compressed into board	Electrical energy, thermal energy
Sanding machine (Scenarios 1, 2)	Board sanding	Electrical energy
Sawing machine (Scenarios 1, 2)	Prepared specification board	Electrical energy
Blower, induced draft fan (Scenarios 1, 2)	Exhaust, ventilation	Electricity, gas
Supply air system (Scenarios 1, 2)	Transportation of fiber raw materials	Electrical energy
Cyclone separator (Scenario 3)	Separation of straw and dust	Electrical energy
Bag filter (Scenario 3)	Dust recovery, gas emissions	Electrical energy
Conveyor (Scenario 3)	Conveying materials	Electrical energy
Boiler (Scenario 3)	Convert chemical energy into thermal energy	Chemical energy $\rightarrow$ thermal energy
Steam turbine (Scenario 3)	Steam enters steam turbine adiabatic expansion to do work to convert thermal energy into mechanical energy	Thermal energy $\rightarrow$ mechanical energy
Generator (Scenario 3)	Converting mechanical energy into electricity	Mechanical energy $\rightarrow$ electrical energy

fossil energy, reduce greenhouse gas emissions, and produce fewer nitrogen oxides by low-temperature combustion [51]. Therefore, the flue gas after dust removal can be directly discharged into the atmosphere through the chimney without desulfurization [52, 53].

The straw is transported to the power generation enterprise through the main road by using a truck, and the fuel used is diesel. At the stage of straw transportation, the pollutant emissions are considered to be the emissions of diesel during production and combustion. According to the emission coefficient of diesel production and combustion, pollutant emissions during transportation can be calculated. The straw direct combustion power generation process is mainly divided into three parts: the collection and treatment of straw, the pretreatment of straw, and the last step is combustion power generation. Straw pretreatment is done after straw collection and treatment. The pretreatment of the power plant is mainly performed to decompose and crush the collected straw. Usually a complete set of equipment is used, including crusher, conveyor, and dust collector (with a bag dust collector at the tail of the boiler). Finally, the power plant pretreatment data and biomass (straw) power generation index are calculated based on the survey, and the direct-fired power generation system is analyzed and calculated. With reference to the literature and specifications, the energy released by burning 1 t of straw for power generation is statistically analyzed and compared with common power generation methods (coal power generation is divided into three steps: coal mining and washing, coal

transportation and storage, and coal power generation), and from [36], the functional units are 1 ton. Data of materials and energy consumption in transportation and production of power generation are shown in Table 7. Table 3 shows the main equipment and energy consumption used in the production process of Scenarios 1, 2, and 3.

*2.3.4. Statement of Scenario 4 (Reference Scenario).* Straw directly burned outdoors will cause serious air pollution problems. Besides, the proportion of straw open burning has a certain relationship with crop yield, geographical location, and income level of residents. In large agricultural provinces with high crop yield, farmers have a higher tendency to choose straw burning in the open air. Secondly, due to the lack of heating in winter, the demand for straw as fuel is insufficient and the possibility of open burning is higher. Open-air incineration of crop straw will emit gas pollutants, resulting in a sharp decline in air quality.

By collecting the existing emission test results, the environmental impact of 1 t straw open-air incineration treatment was evaluated. And the atmospheric pollutant emission factors of various straws were obtained and the average values were taken [56–59]. The results of the straw open burning incineration factors are shown in Table 8.

*2.4. Impact Assessment and Explanation.* In this study, global warming potential (GWP) and nonrenewable energy consumption are used as impact assessment criteria. It is

TABLE 4: LCI data for production of 1 m<sup>3</sup> straw cement-bonded particleboard and wood cement-bonded particleboard.

Process of production	Energy consumption	Data sources
<b>Straw cement-bonded particleboard</b>		
Straw collection and processing	40 km by 30 t trucks	[42–44]
Straw transport to cement board production site	Diesel: 1.12 kg	
Straw processing (preparation of straw, e.g. chips, planing, and screening)	Electricity: 18.7 kWh	[44];
Straw drying	Electricity: 16.7 kWh	
<b>Other materials</b>		
OPC production and transportation to board manufacturing site	60 km by 30 t trucks Diesel: 1.96 kg Electricity: 41.157 kWh	[42–44, 48]
Accelerator production and transportation	Raw coal : 61.32 kg 200 km by 30 t trucks Diesel: 0.47 kg Raw coal: 21.2 kg Crude oil: 24.8 kg	[42–44, 48, 49]
Production processing (e.g., mechanical mixtures, through the diffuser, pressing, adjustment, drying, and other ways and evenly spread on the substrate)	Electricity: 80.8 kWh	[44]
Product completion and processing	Electricity: 49.5 kWh Diesel: 1.537 kg	[42–44]
<b>Wood cement-bonded particleboard</b>		
Wood handling and treatment	40 km by 30 t trucks	[42, 44, 46]
Wood transport to cement board production site	Diesel: 1.25 kg	
Wood treatment (processing and preparation of wood, e.g., chips, planing, and screening)	Electricity: 21.4 kWh	[42–44]
Wood drying	Electricity: 26.2 kWh	
<b>Other materials</b>		
OPC production and transportation to board manufacturing site	60 km by 30 t trucks Diesel: 2.13 kg Electricity: 54.876 kWh	[42–44, 50]
Accelerator production and transportation	Raw coal: 81.76 kg 200 km by 30 t trucks Diesel: 0.56 kg Raw coal: 22.8 kg Crude oil: 25.4 kg	[42–44]
Production processing (e.g. mechanical mixtures, through the diffuser, pressing, adjustment, drying, and other ways and evenly spread on the substrate)	Electricity: 78.4 kWh	[42–44]
Product completion and processing	Electricity: 45 kWh Diesel: 1.4 kg	[42, 44]

TABLE 5: Composition of straw cement-bonded particleboard and the process involved.

Materials	Proportion (%)	Raw materials involved in the process
OPC	53	OPC production and transportation
Straw fiber	38	Straw transport to site, straw drying, and straw processing
Accelerator (CaCl <sub>2</sub> )	5	Accelerator production and transportation
Waterproof agent	1.5	Waterproof agent production and transportation
Adhesive	2.5	Mold dope production and transportation
Finished cement composite board (1 m <sup>3</sup> )	100	Cement-bonded particleboard production processing, finishing process, and on-site handling

TABLE 6: Environmental data for utility systems and cement production.

	Energy consumption	CO <sub>2</sub> (kg)	CO (kg)	C <sub>x</sub> H <sub>y</sub> (kg)	NO <sub>x</sub> (kg)	SO <sub>2</sub> (kg)
Electricity (kWh)	Standard coal: 0.424 kg 0.0124 GJ	0.938	0.00004	0.000072	0.0051	0.00112
Transport (30 t-km)	Diesel: 0.06 L/(km-t) 0.02142 GJ	1.6614	0.0106	0.000094	0.00637	0.000359
Coal (10 <sup>3</sup> kg)	Electricity: 13.89 kWh	—	—	—	—	—
Cement mining (10 <sup>3</sup> kg)	Electricity: 13.89 kWh	—	—	—	—	—
Cement manufacturing (10 <sup>3</sup> kg)	Electricity: 123.3 kWh Coal: 204.4 kg	885	0.0115	0.0273	1.533	0.354

TABLE 7: LCI data for 1 t straw direct combustion and coal-fired power generation.

Process of production	Energy consumption	Data sources
Straw direct combustion power generation		
Straw collection and processing	40 km by 30 t trucks	[42, 43]
Straw transport to power plant	Electricity: 30 kWh Diesel: 2.05 kg	[42, 44] [42, 43]
Straw pretreatment (crushing and drying)	Electricity: 21.2 kWh Raw coal: 44.6 kg	[42, 43, 54, 55]
Combustion power generation	Provided by the system's own power generation, no energy consumption is required	
Coal-fired power generation		
Coal production and processing	40 km by 30 t trucks	[54, 55]
Coal preparation (coal mining and washing)	Electricity: 225 kWh	[42, 43, 54, 55]
Coal transport to power plant	Diesel: 2.04 kg	[42, 43]
Combustion power generation	Provided by the system's own power generation, no energy consumption is required	

TABLE 8: Emission factors of straw open burning.

Crops	Emission factors (g·kg <sup>-1</sup> )						
	CO <sub>2</sub>	CH <sub>4</sub>	CO	NO <sub>x</sub>	SO <sub>2</sub>	NH <sub>3</sub>	PM
Rice	1460.00	3.20	34.70	3.10	2.00	0.78	12.95
Wheat	1460.00	3.40	60.00	3.30	0.85	0.37	7.60
Maize	1350.00	4.40	53.00	4.30	0.44	0.68	11.70
Average value	1423.33	3.67	49.23	3.57	1.10	0.61	10.75

noteworthy that the scenarios studied are modeled using eBalance software and the CLCD database. Generally, a type of environmental impact is affected by several different pollutants, so the input of substances and the discharge of pollutants need to be classified according to the type of environmental impact, and then the potential of environmental impact is calculated, which can be estimated using (1) and (2). Finally, according to the functional unit, the environmental impact and energy consumption in different situations are compared, and the reasons are analyzed. Besides, both straw and wood will produce dust in the crushing process, so the impact of dust is not considered. Using Oracle Crystal Ball software, we simulated the changes of key parameters in the range of ( $\pm 20\%$ ) for 1 million times and obtained the contribution rate of key parameters to the environmental performance of different scenarios.

Environmental impact potential (EIP) is the summation of all associated environmental emission impacts across the system and is expressed as

$$E_P(m) = \sum E_P(m)_n = \sum [Q(m)_n \times E_f(m)_n], \quad (1)$$

where  $E_P(m)$  is the  $m$ th environmental impact potential in the product life cycle,  $E_P(m)_n$  is the  $m$ th environmental impact potential of the  $n$ th emissions,  $Q(m)_n$  is the  $n$ th emissions, and  $E_f(m)_n$  is the  $m$ th environmental impact equivalent factor of the  $n$ th emissions. Finally, the potential impacts of various environmental impacts are integrated.

The formula for calculating the benchmark value of environmental impact standardization is as follows:

$$NE_P(m) = \frac{E_P(m)}{E_R(m)}, \quad (2)$$

where  $NE_P(m)$  is the standardized value of the  $m$ th environmental impact potential,  $E_P(m)$  is the  $m$ th environmental impact potential, and  $E_R(m)$  is the per capita potential of social-environmental impact in the base year.

### 3. Results and Discussion

**3.1. Discovery and Discussion of Scenario 1.** The greenhouse gas (GHG) emissions and nonrenewable energy consumption of 1 m<sup>3</sup> straw particleboard and wood particleboard are compared in Figures 3 and 4. It can be found that about 600 kg CO<sub>2</sub> eq GHG emission is generated in the production process of 1 m<sup>3</sup> straw particleboard, while about 640 kg CO<sub>2</sub> eq GHG emission is related to the 1 m<sup>3</sup> wood particleboard production (Figure 3). For straw or wood particleboard, the contribution to total emissions is, in turn, the production



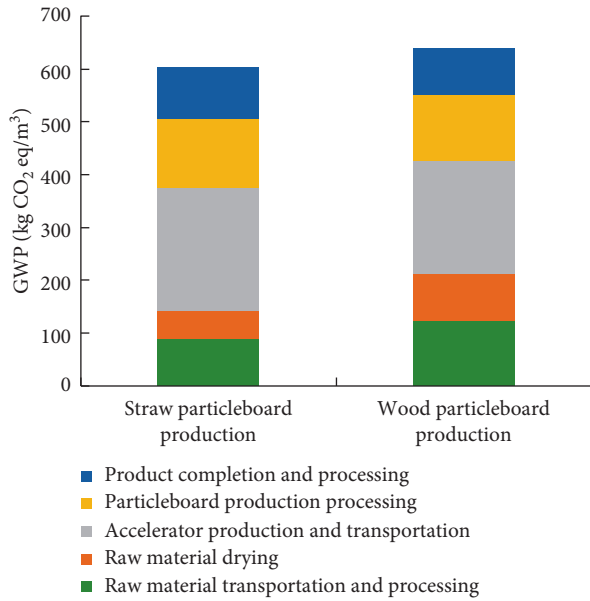


FIGURE 3: Contribution of particleboard production process to GWP impact.

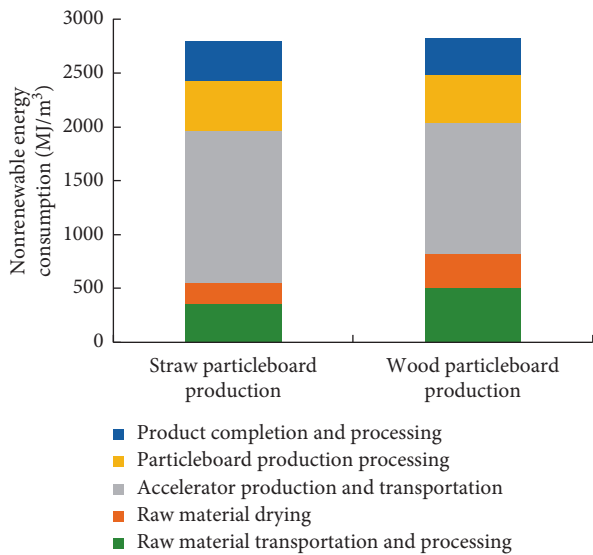


FIGURE 4: Contribution of particleboard production process to nonrenewable energy consumption.

and transportation of other materials such as accelerators, production, and processing (including plate paving, hot pressing, cooling and trimming) and transportation and processing of raw materials (including collection and transportation of raw materials, finishing, and drying). Similarly, the production of 1 m<sup>3</sup> straw particleboard consumes about 2700 MJ of nonrenewable energy, and about 2800 MJ is related to 1 m<sup>3</sup> particleboard produced with virgin wood (Figure 4).

It can be seen from Figures 3 and 4 that the ratio of wood particleboard to straw particleboard is higher in raw material processing and drying because the moisture content of raw wood is higher. The collection, transportation, and drying of

wood greatly increase greenhouse gas emissions and resource consumption in particleboard production, and the drying process needs to make the moisture content below 12% to improve process efficiency and board quality. Besides, there are also significant differences in the transportation and processing of two different raw materials. Comparing straw particleboard with wood particleboard, it is found that the greenhouse gas emissions of straw particleboard are reduced by about 7% (Figure 3). Similarly, straw particleboard reduced nonrenewable energy consumption by about 4% (Figure 4), which might be due to the fact that straw particleboard omitted the steps of the peeling machine, and peeling to make wood, which saved the energy consumption of these two steps compared with the production process of wood board (Table 9).

Juan et al. [33] proposed that, according to the life-cycle assessment (LCA) model, MDF applications could save 193–439 kg of CO<sub>2</sub> equivalent of greenhouse gases (per 700 kg of bales of straw). The application of MDF could avoid the reduction of greenhouse gas emissions by about 36%. Although energy and greenhouse gas emissions might be affected by the moisture content, transportation conditions, and equipment of straw in different regions, the results obtained in this study were consistent with the above results.

**3.2. Discovery and Discussion of Scenario 2.** Given the data collected in Scenario 2, the results of LCA are shown in Figures 5 and 6. 1 m<sup>3</sup> of cement-bonded particleboard releases about 980 kg CO<sub>2</sub> eq GHGs, while wood cement-bonded particleboard produces about 1100 kg CO<sub>2</sub> eq GHGs. Straw cement-bonded particleboard reduces the greenhouse gas equivalent of about 120 kg CO<sub>2</sub> eq GHGs compared with wood cement-bonded particleboard. In straw cement-bonded particleboard production, raw material transportation and treatment accounts for 10% of greenhouse gas emissions, OPC production machine transportation account for 48%, production process accounts for 35%, and chemical catalyst accounts for 7%. For straw cement-bonded particleboard, cement production and transportation contribute most to total emissions. The production and transportation of OPC in wood cement-bonded particleboard accounted for 51% of the total, which is due to the largest amount and proportion of cement used in the production of cement-bonded particleboard.

Likewise, the production of 1 m<sup>3</sup> wood cement-bonded particleboard consumes about 5500 MJ of nonrenewable energy, which is higher (about 15%) than the straw cement-bonded particleboard production. In the production of straw cement-bonded particleboard, the transportation and treatment of raw materials account for 8% of nonrenewable energy consumption, the production and transportation of OPC account for 36%, the production process accounts for 26%, and the use of chemical catalysts accounts for 30%. For straw cement-bonded particleboard, the most important contribution to total emissions is the production and transportation of OPC, accounting for 41% of the total. Therefore, it is observed that the production of straw cement-bonded particleboard has a less environmental impact.

TABLE 9: Comparative contribution to the production of straw and wood particleboard.

Processes	GHG emission (%)		Nonrenewable energy consumption (%)	
	Straw particleboard	Wood particleboard	Straw particleboard	Wood particleboard
Raw materials transportation and processing	14.77	19.47	12.92	17.79
Raw material drying	8.71	13.63	6.72	11.06
Accelerator production and transportation	38.88	33.62	50.53	43.50
Particleboard production processing	21.48	19.43	16.57	15.76
Product completion and processing	16.16	13.85	13.26	11.89
Total	100.00	100.00	100.00	100.00

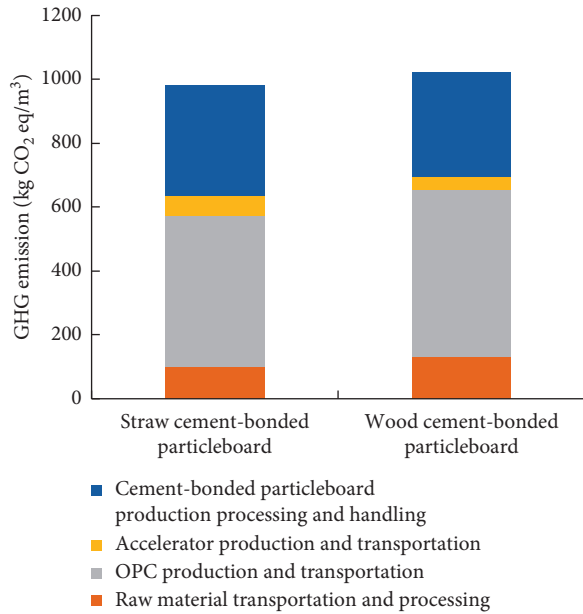


FIGURE 5: Contribution of cement-bonded particleboard production process to GWP impact.

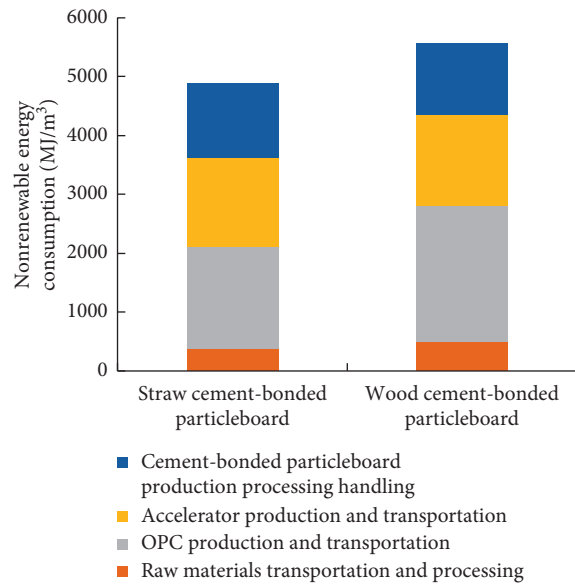


FIGURE 6: Contribution of cement-bonded particleboard production process to nonrenewable energy consumption.

The comparative analysis of the production of straw cement-bonded particleboard and wood cement-bonded particleboard is shown in Table 10.

Eternit [60] demonstrated the energy consumption and greenhouse gas emissions of cement particle board (for environmental product declarations). The study found that producing 1 ton of CBP and OPC (excluding carbon fixation) from logs in Germany consumed about 7100–14000 MJ of nonrenewable energy and emitted about 800–1100 kg of carbon dioxide equivalent greenhouse gases. Although there was no LCA-related research on straw cement cement-bonded particleboard, the related research of wood cement particleboard provides a reference.

**3.3. Discovery and Discussion of Scenarios 3 and 4.** In this study, the life cycle of a ton of straw and a ton of coal power generation are compared and analyzed, and the results of GWP and total emissions of nonrenewable resources consumption in the power generation process are compared, as shown in Figures 7 and 8. As can be seen from Figure 7, the GHG emissions of 1 t straw direct combustion power generation are approximately 2100 kg CO<sub>2</sub> eq GHGs, while that of 1 t coal-fired power generation is approximately 3000 kg CO<sub>2</sub> eq. The GHG emissions of straw direct combustion power generation are about 30% lower than that of coal-fired power generation. In straw direct combustion power generation, the straw collection and transportation accounts for 5% of the total GHG emissions, the pretreatment of straw (crushing, drying, and shaping) accounts for 14%, and the combustion power generation accounts for 81%. For straw direct combustion power generation, the electric power generation process contributes most to the total emissions. For coal-fired power generation, coal treatment, transportation and storage, and coal-fired power generation accounted for 19%, 1%, and 80% of the total emissions, respectively. The power generation process accounted for the largest proportion, and the pollutant emissions are large, which would pollute the environment (Table 11).

From Figure 8, it can be seen that 1 t straw direct combustion power generation consumes about 1400 MJ nonrenewable resources, which is about 36% lower than coal-fired power. In straw direct combustion power generation, straw collection and transportation, straw pretreatment, and combustion power generation accounted for

TABLE 10: Comparative contribution to the production of straw and wood cement-bonded particleboard.

Processes	GHG emission (%)		Nonrenewable energy consumption (%)	
	Straw cement-bonded particleboard	Wood cement-bonded particleboard	Straw cement-bonded particleboard	Wood cement-bonded particleboard
Raw materials transportation and processing	5.73	6.28	4.51	4.51
Raw material drying	4.37	6.59	3.15	4.35
OPC production and transportation	48.39	50.91	35.71	41.49
Accelerator production and transportation	6.25	4.17	30.71	28.11
Cement-bonded particleboard production processing	21.16	19.73	15.24	13.00
Product completion and processing	14.10	12.32	10.68	8.54
Total	100.00	100.00	100.00	100.00

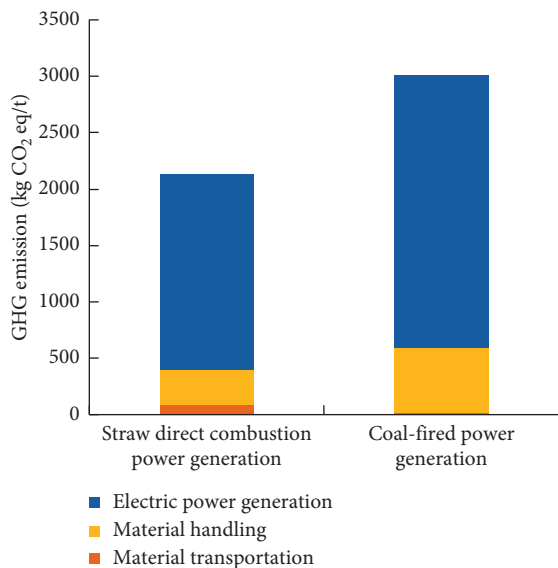


FIGURE 7: Contribution of different ways of power generation to GWP impact.

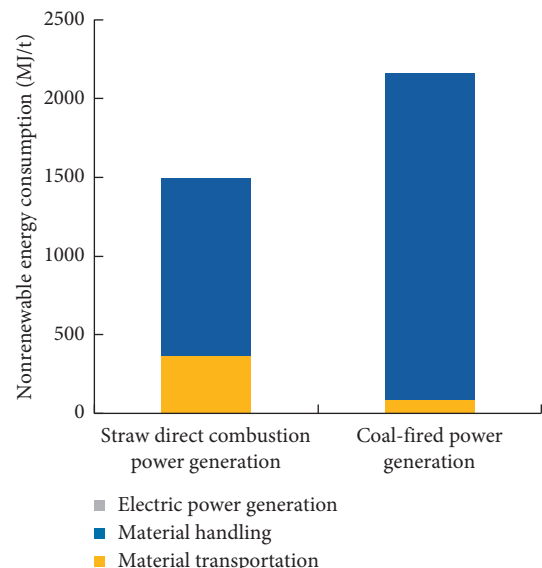


FIGURE 8: Contribution of different ways of power generation to nonrenewable energy consumption.

25%, 75%, and 0 of the total consumption, respectively. For straw direct combustion power generation, the straw pretreatment process contributes the most to the total emissions, including the smashing, drying, and shaping of straw. Similarly, coal mining and washing, transportation and storage, and coal-fired power generation accounted for 95%, 5%, and 0% of the total emissions, respectively. The coal mining and washing process accounted for the largest proportion. Coal mining and washing generally extracted coal from the producing area and removed impurities from coal, and the main energy consumption is electricity (Table 11).

Liu et al. [61] proved that if there were 400 million tons of waste straw in China could replace 200 million tons of coal, then 291 watt-hours (TWh) of straw could be produced each year, which saved 193 million tons of CO<sub>2</sub> annually. Shafie et al. [30] calculated that straw power generation could save about 1.79 kg/kWh of greenhouse gas emissions compared to coal-fired power generation and natural gas

power generation. The improvement of energy efficiency of the straw pretreatment equipment will lead to a reduction in greenhouse gas emissions and energy consumption in the life cycle of straw power generation. Although the energy consumption and CO<sub>2</sub> emissions were severely affected by local energy sources and equipment, the results obtained in this study were consistent with the above findings.

Scenario 4 (straw open burning), rice, corn, and wheat straw are the main sources of emissions from the open burning of straw in China. Due to the differences in crop yield and the proportion of straw open burning and combustion efficiency, the contribution rates of different crop types to pollutant emissions are also different. Therefore, the emission factor is taken as the average value of three main crop types. The carbon emissions of straw incineration in the open are very high, with CO<sub>2</sub> as high as 1423 g/kg, followed by 49 g/kg of CO gas and 10 g/kg of PM. These three kinds of gases are high pollutant gases, especially CO<sub>2</sub>, which is much higher than other pollutants. It is estimated that the GHG

TABLE 11: Comparative contribution analysis for different electric power generation processes.

Processes	GHG emission (%)		Nonrenewable energy consumption (%)	
	Straw direct combustion power generation	Coal-fired power generation	Straw direct combustion power generation	Coal-fired power generation
Material transportation	4.32	0.49	24.40	4.03
Material handle	14.26	19.26	75.60	95.97
Electric power generation	81.42	80.25	0	0
Total	100.00	100.00	100.00	100.00

emission of about 2642 kg CO<sub>2</sub> eq is related to 1 t straw burning in the open air, which is much higher than the other three scenarios. Compared with open burning, the biggest advantage of strawboard and straw power generation is to reduce carbon emissions and PM emissions.

**3.4. Comparative Analysis of Different Straw Management Strategies.** The difference of nonrenewable energy consumption and gas emission indices under different straw resource utilization scenarios is compared in Figures 9 and 10. The environmental impact of different management scenarios is shown in Table 10. All are discussed under the functional unit of 1-ton straw. Figure 9 shows that the nonrenewable energy consumption of straw cement-bonded particleboard is the highest and straw direct combustion power generation consumption is the lowest mainly because of the large proportion of OPC, accelerators, and other materials in the production of straw cement-bonded particleboard, which consumes more energy.

CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and so on are the main gases causing GWP. SO<sub>2</sub> and NO<sub>x</sub> are the main gases causing the acidification potential (AP). The emission index of open burning of CO<sub>2</sub>, SO<sub>2</sub>, or other gases is much higher than that of other scenarios. Straw direct combustion power generation is much larger than that of straw particleboard and straw cement-bonded particleboard. The emission index is mainly because the straw combustion process has the greatest impact on the environment in direct combustion power generation (Figure 10). Compared with other scenarios, the GWP and AP comparisons of numerical values are straw open burning > straw direct combustion power generation > straw cement-bonded particleboard > straw particleboard. The greenhouse effect and acidification effect of straw open burning are far greater than those of other scenarios, but the impact of straw particleboard and straw cement-bonded particleboard on the environment is relatively small (Table 12).

According to the related research, Scenarios 1, 2, and 3 are feasible in the technology of using the waste straw [4, 22, 62]. It is most advantageous to convert waste straw into green products and produce them in nearby factories because it reduces the long-distance supply chain and its associated impacts. Therefore, straw open burning has caused great environmental pollution in the light of greenhouse gas emissions, acidification effects, and particulate matter emissions. Making straw into board or fuel can

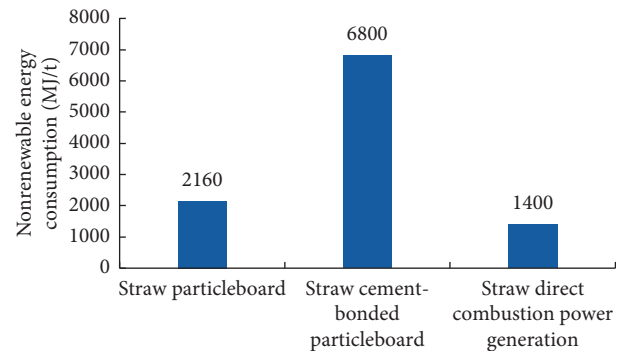


FIGURE 9: Comparison of nonrenewable energy consumption in Scenarios 1, 2, and 3.

improve the environmental impact. From the perspective of environment, straw building materials have little environmental influence and can be widely used.

**3.5. Sensitivity Analysis.** Using Oracle Crystal Ball software, the key parameters are changed within  $\pm 20\%$  for 1 million times and obtained the contribution rate of key parameters to the environmental performance under different scenarios as shown in Figure 11. From the figure, we can see that the power consumption of the molding process, the distance of straw transportation, and the power consumption in the shaping process are the three main elements affecting the environmental performance of Scenario 1. The total contribution rate of the three factors to GWP is 79.4%. The contribution rate of the power consumption in the shaping process to the environmental emission change of the system reaches 36.7%. In Scenario 2, the power consumption of the shaping process, straw transportation distance, and OPC transportation distance are the primary factors. The total contribution proportion of the three factors to GWP is 85.3%. Among them, the contribution rate of power consumption in shaping process to the change of system environment emission is 33.7%. In Scenario 3, the contribution rates of straw pretreatment power consumption and straw transport distance are 58.3% and 41.7%, respectively.

Reducing the impact of raw material consumption is comprehensive and can reduce the input of straw transportation and pretreatment process at the same time. Therefore, it is obliged to control the water content of raw stocks, reduce the loss of raw material collection, and

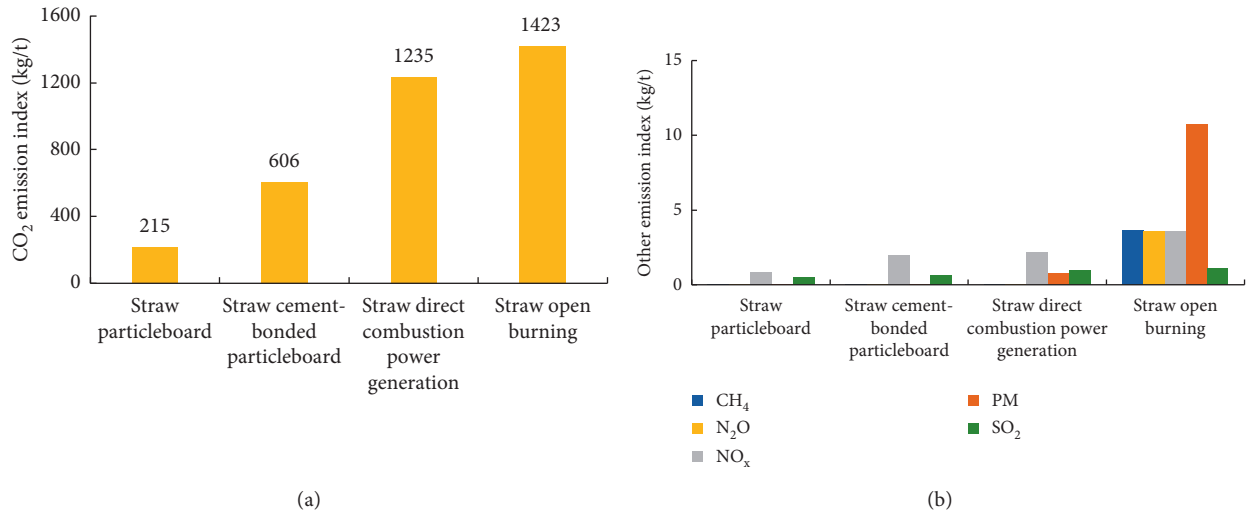


FIGURE 10: Comparisons of gas emission index under different scenarios: (a) comparisons of CO<sub>2</sub> emission index and (b) comparisons of other gas emission index.

TABLE 12: Comparison of environmental impact trends among different management scenarios.

Scenario	GWP (kg CO <sub>2</sub> eq/t)	AP (kg SO <sub>2</sub> eq/t)
1	→2000	→2.5
2	→1620	→1.6
3	→600	→1.1
4	2600	3.6

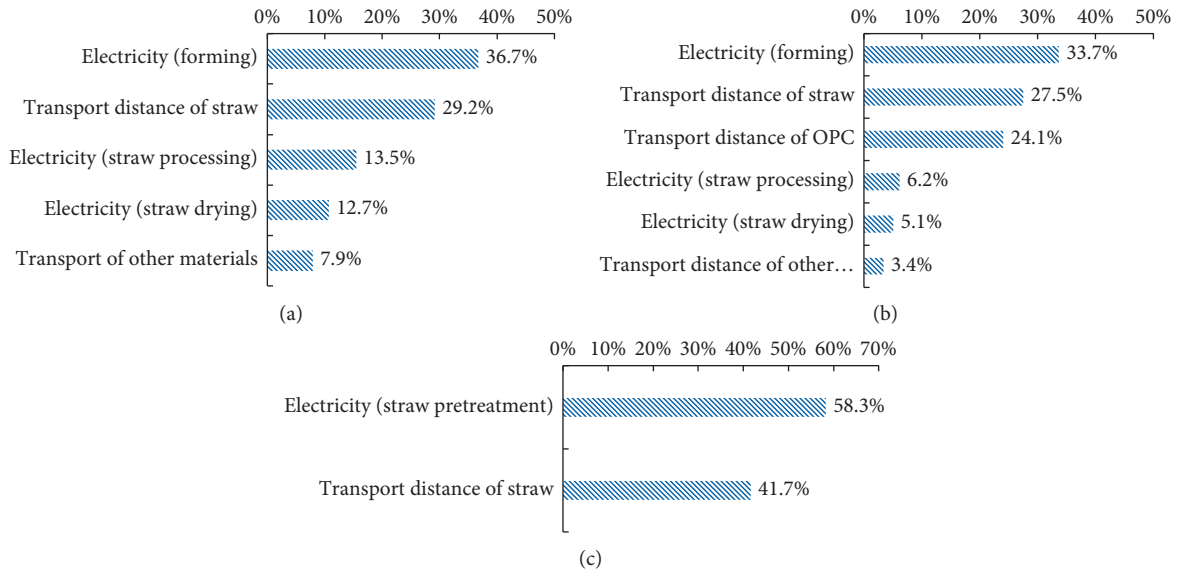


FIGURE 11: Sensitivity analysis of contribution to variance in greenhouse gas emissions of Scenario 1 (a), Scenario 2 (b), and Scenario 3 (c).

improve the utilization of raw stocks. The contribution rates of power consumption (including crushing, screening, shaping, and packaging) are 62.9%, 45%, and 58.3% of the change in greenhouse gas emissions under three scenarios, respectively. Therefore, the emission reduction of the system depends on the development of energy-saving technologies in the energy conversion process (especially in the shaping process). In addition, controlling the transportation distance

of other materials is also essential to ameliorate the overall environmental protection level of the system.

#### 4. Conclusions

In this study, the inventory data of the four typical scenarios about recycling and disposal of straw resources were calculated by LCA. Comparable studies were conducted on the

greenhouse gas emissions, acidification effects, and nonrenewable energy consumption of each scenario. Some specific conclusions are summarized as follows:

- (a) Reusing straw on the fiberboard production or combustion power generation is a feasible pathway from the environmental and technical view. Production and transportation process of catalysts, OPC, and the combustion power generation process have been the largest parts of impacting on the environment in Scenarios 1, 2, and 3, respectively. Enterprises are suggested to improve their technological approaches to reduce pollutant emissions following these aspects.
- (b) From the perspective of environmental impact, the straw particleboard is the optimal scheme for recycling and reusing crop straw resources. The open-air burning of straw generates the highest pollutant emissions with the greatest impact on GWP and AP, which is the least desirable scheme. The government is supposed to emphasize on air pollution caused by the open burning of crop straw. It is important for the government to establish the comprehensive utilization industry chain, effective policy subsidies, and incentive policies.
- (c) According to the results of the sensitivity analysis, the power consumption during the forming process and straw transportation distance are the main factors affecting the environmental performance in Scenarios 1 and 2. It is necessary to strengthen the energy-saving technology for molding and control the radius of straw transportation.

## Data Availability

The test data are included within the article and can be made freely available.

## Conflicts of Interest

The authors declare no conflicts of interest.

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