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Bioenergy Production from Rapeseed Straw: A Feasibility Study

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Abstract Rapeseed straw is a common type of agricultural waste. We want to see if it can be used for bioenergy, such as ethanol, biogas and protein, etc. In the experiment, we pre-treated the straw with water heat, dilute acid and mechanical methods. This way, its structure would become easier to decompose and the subsequent conversion efficiency would also be higher. Under the best conditions, the ethanol output can reach 12.2 g/L, and the methane output can reach up to 365 N mL/g of volatile solids. The remaining by-products can also be used to produce proteins or some valuable chemicals. We also attempted mechanical crushing and anaerobic digestion of straw and livestock manure together, which can increase gas production and energy recovery. However, the high ash content, high chlorine content and high sulfur content of straw still pose challenges. By improving pretreatment and process combinations, there is an opportunity to increase energy output and reduce greenhouse gas emissions. The aim of this study is to provide data and scheme references for the utilization of rapeseed straw in the field of sustainable energy.
Keywords Rapeseed straw; Bioenergy; Biological refining; Pre-treatment; Sustainability

1 Introduction

With the increasing global demand for renewable energy, the reuse of agricultural waste is becoming increasingly important. Rapeseed straw is the main by-product left after rapeseed harvest, and its quantity is very large. In the past, people often burned directly in the fields. This not only wasted resources but also polluted the air and increased greenhouse gas emissions (Passoth and Sandgren, 2019; Abbasi-Riyakhuni et al., 2025). Therefore, finding more efficient utilization methods, especially in the field of bioenergy, is beneficial to both environmental protection and economic development.

Although rapeseed straw has a high potential for biomass energy, it has a high lignin content and a compact structure, making it difficult to decompose. This will reduce the efficiency of biological transformation and is also a major challenge for industrial utilization. Research has found that if proper pretreatment is not carried out, straw is difficult to be enzymatically hydrolyzed and fermented, thereby affecting the output of fuels such as ethanol, biogas, biodiesel, and some high-value chemicals. There are still many problems in terms of its physicochemical properties, pretreatment methods, transformation processes and economic feasibility (Lopez-Linares et al., 2015; Passoth and Sandgren, 2019; Stolarski et al., 2024; Abbasi-Riyakhuni et al., 2025).

This review mainly sorts out and analyzes the new progress of rapeseed straw in bioenergy production, with a focus on introducing pretreatment technologies, conversion routes (such as ethanol, biogas, biodiesel, etc.), energy output and by-product utilization, etc. The technical and economic conditions of different processes will also be compared to identify their advantages and problems, and future development directions will be proposed to provide references for the high-value utilization of agricultural waste and the green energy industry (Luo et al., 2011; Lopez-Linares et al., 2015; Kuglarz et al., 2018; Elsayed et al., 2020; 2022; Yang et al., 2024).

2 Rapeseed Straw as a Biomass Resource

2.1 Production potential

Rapeseed (*Brassica napus* L.) is one of the common oil crops in the world, and there is a large amount of straw. At the current planting level, rapeseed can produce approximately 4.2 tons of dry straw per hectare (Elsayed et al., 2022; Malatʼ ak et al., 2024). In some places, the figure would be between 2.8 and 4.5 tons per hectare (Malatʼ ak et al., 2024). So much straw provides sufficient raw materials for the production of biofuels, biogas and biochar, etc. (Karaosmanoglu et al., 1999; Elsayed et al., 2022; Malatʼ ak et al., 2024; Suchocki, 2024) (Figure 1).

Figure 1 *Brassica napus* (Adopted from Suchocki, 2024)

2.2 Composition and properties

Rapeseed straw is mainly composed of cellulose, hemicellulose and lignin, with an approximate ratio of 1:2:0.8 (lignin: cellulose: hemicellulose), and also contains some ash (Hou et al., 2023). It has a high content of cellulose and hemicellulose, and is very suitable for saccharification and biofuel conversion (Hou et al., 2023; Yang et al., 2024; Tang et al., 2025). The carbon-nitrogen ratio of rapeseed straw is approximately 153.82, and the pH value is around 6.05. All these will affect its effect in anaerobic digestion and microbial decomposition (Witaszek et al., 2025). Its high calorific value is approximately 17.36 MJ/kg, with a high carbon content. After pyrolysis, the oxygen content will significantly decrease, which is beneficial for improving fuel quality (Malatʼ ak et al., 2024). However, its ash and chlorine content is not low either. Attention should be paid during combustion or pyrolysis (Hou et al., 2023; Malaťak et al., 2024).

2.3 Seasonality and availability

The output and supply of rapeseed straw are mainly related to the harvest season. Generally, a large amount of straw is produced in a concentrated manner after the summer harvest (Malatʼ ak et al., 2024). Rapeseed has a large planting area in Europe, China and other places. The straw resources are abundant and concentrated, which is convenient for collection and large-scale utilization (Malatʼ ak et al., 2024; Suchocki, 2024). In addition, the distribution of straw in the field and the way it is collected will also affect its cost and sustainability in energy utilization (Elsayed et al., 2022; Suchocki, 2024).

3 Technological Pathways for Bioenergy Production

3.1 Thermochemical conversion

Thermochemical conversions include incineration, gasification and pyrolysis. slow pyrolysis (slow pyrolysis) can turn rapeseed stalks into biooil and biochar. Studies have found that under the conditions of 650 °C and a heating rate of 30 °C/min, pyrolysis of rapeseed straw and stems can achieve the highest liquid yield, and bio-oil has the potential as fuel (Karaosmanoglu et al., 1999). Biochar has a high carbon content and good reactivity, and can be used as clean solid fuel (Karaosmanoglu et al., 2000). However, the high content of chlorine, sulfur and ash in straw will bring some problems in thermochemical utilization (Stolarski et al., 2024) (Figure 2).

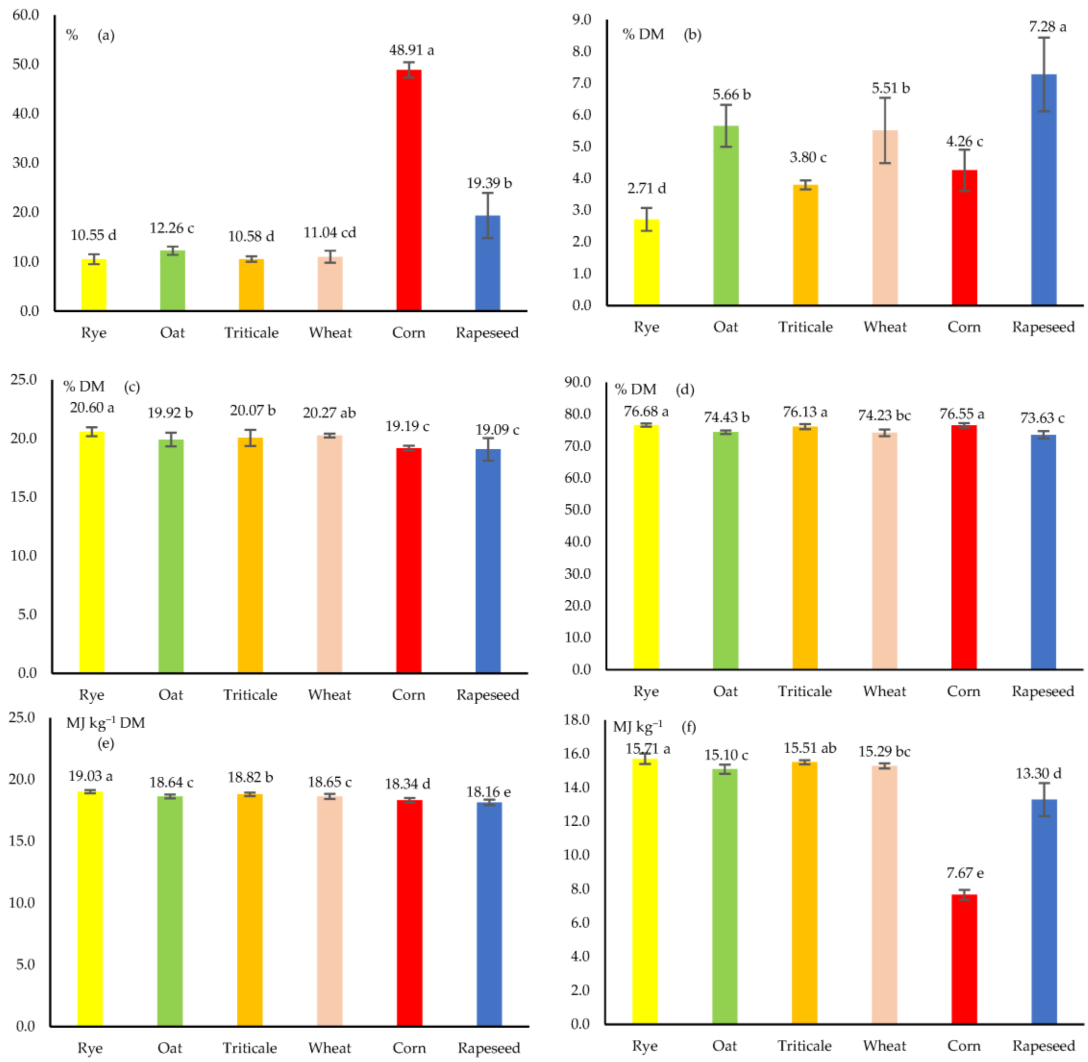

Figure 2 Thermophysical characteristics of the straw types under study, mean values of the three harvest years (Adopted from Stolarski et al., 2024)

Note: (a) Moisture content; (b) ash content; (c) fixed carbon content; (d) volatile matter content; (e) higher heating value; (f) lower heating value; a, b, c, d, e, denote homogeneous groups for the straw type, separately for each attribute; error bars denote standard deviation (Adopted from Stolarski et al., 2024)

3.2 Biochemical conversion

The main biochemical transformations include anaerobic digestion and fermentation. Rapeseed straw can produce biogas through anaerobic digestion, and the output of methane is affected by the size of raw material particles and the carbon-nitrogen ratio. Mechanical pretreatment can make the gas production efficiency higher (Witaszek et al., 2025). When producing bioethanol, pretreatment with dilute acid combined with enzymatic hydrolysis can yield very high glucose and ethanol (ethanol yield can reach 122~125 kg/Mg of straw), and the by-products can be further fermented to produce high-value chemicals such as succinic acid (Lopez-Linares et al., 2015; Kuglarz et al., 2018; Tan et al., 2020). By using the integrated biorefining process, ethanol, biogas and fungal protein can be produced simultaneously, greatly improving the energy recovery rate (Luo et al., 2011; Abbasi-Riyakhuni et al., 2025).

3.3 Pre-treatment technologies

Rapeseed straw has a compact structure and a high content of lignin, so effective pretreatment must be carried out first to enhance the efficiency of enzymatic hydrolysis and fermentation. Common methods include hydrothermal, dilute acid, alkaline, steam blasting and combined chemical pretreatment. Hydrothermal pretreatment (120 °C ~180 °C) can significantly increase the specific surface area and porosity of straw, making it easier for enzymes to enter and thereby increasing the yields of ethanol and methane (Abbasi-Riyakhuni et al., 2025). Dilute acid and steam blasting can release cellulose, increase saccharification rate and ethanol yield (Lopez-Linares et al., 2015; Kuglarz et al., 2018; Tan et al., 2020). Combined pretreatment (such as organosilicon surfactant combined with H_2O_2- p-toluenesulfonic acid) can efficiently remove lignin and hemicellulose, with the maximum saccharification rate reaching 87.3% (Yang et al., 2024). Mechanical pretreatment (such as crushing and adjusting particle size) can also improve the effect of anaerobic digestion (Witaszek et al., 2025).

4 Environmental and Socioeconomic Considerations

4.1 Environmental benefits

Producing bioenergy from rapeseed straw has obvious benefits for the environment. Compared with fossil fuels or direct incineration, this utilization method can significantly reduce greenhouse gas (GHG) emissions (Wang et al., 2018; Shi et al., 2023; Fang et al., 2024). Through comprehensive biorefining, straw can be converted into various fuels such as ethanol, biogas and biodiesel. This can not only increase energy output, but also reduce pollution (Luo et al., 2011; Elsayed et al., 2020; Abbasi-Riyakhuni et al., 2025). The results of life cycle assessment show that, compared with crops such as sunflowers, rapeseed bioenergy systems have higher ecological efficiency and produce less greenhouse gases per unit of economic value (Forleo et al., 2018). In addition, replacing energy crops with crop residues such as straw can reduce the consumption of land and water, which is helpful for promoting sustainable agriculture (Fang et al., 2024).

4.2 Economic factors

Rapeseed straw also has certain economic advantages. The comprehensive biorefining model shows that if the entire rapeseed processing plant produces multiple biofuels simultaneously, the energy recovery efficiency can reach 60%, while the traditional biodiesel process is only 20% (Luo et al., 2011). Regional forecasts indicate that the profits of this industry are considerable, and some places can net a profit of 2.2 billion US dollars in 15 years (Wang et al., 2018). The economic benefit per kilogram of greenhouse gas emissions brought by rapeseed is higher than that of sunflower, indicating that its economic return is better when the environmental impact is relatively small (Forleo et al., 2018). Furthermore, this industry can also bring about many job opportunities. The regional bioenergy sector alone is expected to create 166,000 new job opportunities (Wang et al., 2018).

4.3 Policy and regulatory support

Policies and regulations have a significant impact on the development of rapeseed straw bioenergy. The government's planning, support and supervision will directly affect farmers' choices in straw management and energy utilization. Setting clear straw utilization targets, establishing standardized markets, promoting agricultural mechanization and land consolidation can all increase the collection rate and utilization rate of straw (Del Valle et al., 2022). Encouraging the collection and transformation of crop straw instead of open-air burning or leaving it in the fields is crucial for achieving environmental and economic benefits (Wang et al., 2018; Del Valle et al., 2022). These policy measures can help make better use of biomass resources and also contribute to achieving the sustainable development goals.

5 Challenges and Limitations

5.1 Technical challenges

There are many technical challenges in producing bioenergy from rapeseed straw. Rapeseed straw is a kind of lignocellulosic biomass with a very tight structure and is not easy to decompose. If no pretreatment is carried out, it is difficult for enzymes and microorganisms to enter, and the transformation efficiency will be very low (Passoth and Sandgren, 2019; Wang et al., 2023; Abbasi-Riyakhuni et al., 2025). High-temperature hydrothermal, dilute acid, physical plus chemical methods can significantly increase the yield of enzymatic hydrolysis and fermentation, but they will make the process more complex and the cost higher (Tan et al., 2020; Wang et al., 2023; Abbasi-Riyakhuni et al., 2025). Fermentation with high solid content may also encounter problems such as moisture control, uneven mixing and inhibitor accumulation, thereby affecting the output of fuels such as ethanol (Tan et al., 2020). In anaerobic digestion and the refining of multi-process products, the stability of the process and the treatment of by-products are also technical difficulties that need to be solved (Luo et al., 2011; Elsayed et al., 2020; Abbasi-Riyakhuni et al., 2025).

5.2 Economic risks

The economic feasibility of bioenergy from rapeseed straw is influenced by multiple factors. The high cost of pretreatment and enzymes is a major economic bottleneck for industrialization (Passoth and Sandgren, 2019; Wang et al., 2023). The collection, transportation and storage of straw all require a large amount of infrastructure, which is difficult for small-scale farmers or small enterprises to afford. Straw may also compete for resources with feed, building materials and other uses, pushing up raw material prices and affecting project profits. Market price fluctuations, unstable policy subsidies, and long payback period of investment will also increase investment risks (Forleo et al., 2018; Ren et al., 2019).

5.3 Policy and infrastructure gaps

Insufficient policies and infrastructure are also the main obstacles to promoting bioenergy from rapeseed straw. At present, in many places, the ban on straw burning mainly relies on administrative orders, but there is a lack of long-term and effective economic incentives and supervision mechanisms. Therefore, the resource utilization rate of straw is not high (Ren et al., 2019; Del Valle et al., 2022). The regional facilities for straw collection, transportation, storage and processing are not yet complete. There is no unified planning and a lack of large-scale investment. It is difficult for farmers and local governments to complete them alone (Ren et al., 2019). The existing policies are rather fragmented in terms of fiscal subsidies, carbon trading, market access, etc., and lack a stable feedback mechanism, making it difficult to support the sustainable development of the industry (Ren et al., 2019; Del Valle et al., 2022). Therefore, to promote the long-term development of rapeseed straw bioenergy, it is necessary to improve the policy system, increase infrastructure construction, and optimize resource allocation.

6. Case Study: Bioenergy Production from Rapeseed Straw in [Selected Region]

6.1 Project background

The Yangtze River Basin is an important major rapeseed production area in China. There are many winter fallows fields here, and the output of rapeseed straw is also very large. In order to develop renewable energy and reduce the pollution caused by straw burning, the local area has carried out a feasibility study on producing bioenergy from rapeseed straw. Using fallow land in winter to grow rapeseed and collect straw not only makes full use of the land, but also provides a stable source of raw materials for the bioenergy industry (Liu et al., 2018).

6.2 Feedstock supply chain

The area of fallow land in the Yangtze River Basin is approximately 24.93 million hectares, with an annual rapeseed output of about 46.41 million tons. The straw resources are concentrated and abundant. The collection of straw mainly relies on mechanical harvesting and transportation, and is combined with farmers' cooperatives and bioenergy enterprises, forming a relatively complete supply chain system. Due to the obvious seasonality of straw, it is necessary to arrange storage, transportation and pretreatment reasonably in order to ensure year-round production (Liu et al., 2018; Stolarski et al., 2024).

6.3 Technology adopted

The local area mainly adopts biochemical conversion technologies, including anaerobic digestion (biogas production), bioethanol fermentation and biodiesel production. Before conversion, straw needs to be mechanically crushed and pre-treated with thermochemical or dilute acid to enhance the availability of cellulose, and then undergo enzymatic hydrolysis and fermentation. Some projects also attempted to use black soldier fly larvae to process straw and livestock manure together, and simultaneously produce biogas, protein and fat to achieve resource utilization of waste (Elsayed et al., 2020; Tan et al., 2020; 2022; Abbasi-Riyakhuni et al., 2025).

6.4 Performance outcomes

After optimized pretreatment of rapeseed straw, the methane yield in anaerobic digestion can reach 132.9-365 Nm^3/ ton of volatile solids, the ethanol yield can be as high as 12.2 g/L, and the biodiesel yield is approximately 689.4 kg/ hectare. The energy output efficiency (EROEI) is between 1.52 and 1.84, and the greenhouse gas reduction effect is significant, reducing 23.28 million tons of carbon dioxide equivalent annually (Liu et al., 2018; Elsayed et al., 2022; Abbasi-Riyakhuni et al., 2025; Witaszek et al., 2025) (Figure 3).

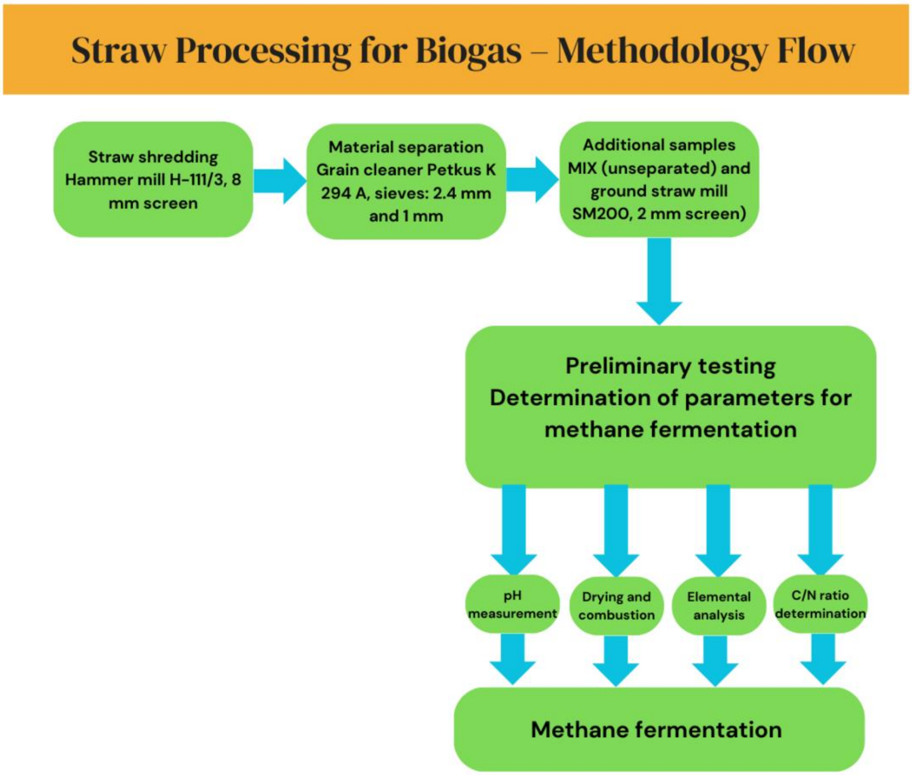

Figure 3 Graphical abstract of the research methodology for straw processing in biogas production (Adopted from Witaszek et al., 2025)

6.5 Economic viability

In the Yangtze River Basin, bioenergy enterprises have a relatively solid foundation for development, and nearly 600 related enterprises can be located here. With abundant raw materials, stable energy output, coupled with policy subsidies and carbon reduction benefits, the overall economic performance of the project is quite good. Products such as biogas, ethanol and biodiesel can also replace some fossil energy and improve the economic benefits of rural areas (Felten et al., 2013; Liu et al., 2018).

6.6 Lessons learned

(1) The costs of straw collection and logistics are high, and the supply chain needs to be optimized. (2) The high cellulose and high ash content characteristics of straw pose certain challenges to equipment and processes, and the pretreatment and fermentation technologies need to be continuously improved. (3) Multi-production and collaborative processing can enhance resource utilization and economic benefits. (4) Policy support and market mechanisms are very important for the long-term development of the project (Liu et al., 2018; Stolarski et al., 2024).

7 Future Perspectives

7.1 Technological innovations

To make efficient use of rapeseed straw, continuous technological improvements are needed. In recent years, the bio-refining technology has developed rapidly, which can convert rapeseed straw into a variety of products such as ethanol, biogas, succinic acid and fungal protein. Hydrothermal pretreatment, dilute acid pretreatment and enzymatic hydrolysis techniques can significantly increase sugar yield and fuel output, and also enhance energy recovery efficiency (Luo et al., 2011; Kuglarz et al., 2018; Passoth and Sandgren, 2019; Abbasi-Riyakhuni et al., 2025). In addition, biotransformation methods such as black soldier fly larvae can simultaneously produce biodiesel and protein, enabling more efficient utilization of waste (Elsayed et al., 2020; 2022). In the future, the energy utilization technology of rapeseed straw will be further upgraded by improving microbial strains, optimizing enzyme preparations and enhancing the value of by-products (Passoth and Sandgren, 2019; Aragonés et al., 2022).

7.2 Integration with circular economy

The energy utilization of rapeseed straw is highly consistent with the concept of circular economy. By using biorefining and polyproduction models, not only can energy, chemicals and feed be obtained simultaneously, but also waste and pollution can be reduced (Luo et al., 2011; Passoth and Sandgren, 2019; Aragonés et al., 2022; Abbasi-Riyakhuni et al., 2025). By-products such as organic fertilizers, protein feed and biochar can recycle nutrients, improve soil and increase carbon sinks (Ren et al., 2019; Cowie, 2020). Next, it is necessary to enhance the full life cycle assessment, improve the indicator system for recycling, and maximize the environmental, economic and social benefits (Cowie, 2020; Arsic et al., 2023).

7.3 Policy directions

Policies are of great significance for the sustainable development of rapeseed straw bioenergy. Current subsidies, tax incentives, carbon trading and other measures have promoted industrialization, but there is still room for improvement in the cost of second-generation biofuels (Ren et al., 2019; Wang et al., 2022). Future policies can focus on: improving the infrastructure for straw collection and supply chains, promoting cross-regional mechanized operations and logistics optimization; Establish diversified incentive mechanisms to encourage high-value utilization of by-products and carbon reduction; Combining the goals of circular economy and carbon neutrality, formulate a long-term and stable policy system to achieve a win-win situation for agriculture, energy and the environment (Ren et al., 2019; Cowie, 2020; Wang et al., 2022; Arsic et al., 2023).

8 Concluding Remarks

Existing research indicates that it is feasible to use rapeseed straw as a raw material for bioenergy, and there are many ways to utilize it. After physical, chemical or biological pretreatment, rapeseed straw can be converted into various energy sources such as bioethanol, biodiesel, biohydrogen and methane. The energy recovery efficiency can reach up to 60%, which is much higher than the 20% of the traditional biodiesel process. Comprehensive utilization of straw can not only increase energy output but also reduce greenhouse gas emissions, with the reduction rate ranging from 9% to 29%. At the same time, it can also enable agricultural waste to be utilized at a higher value.

In terms of policy, efforts can be made to promote the industrialization of rapeseed straw bioenergy, improve the collection, transportation and subsidy mechanisms, and encourage the adoption of multi-product bio-refining models to reduce emissions and drive rural economic development. In terms of research, the pretreatment process can be further improved, such as hydrothermal/dilute acid combined with alkali treatment, mechanical crushing, etc., to enhance the saccharification rate and conversion efficiency. At the same time, attention should be paid to the utilization of by-products and the assessment of environmental impacts. In terms of industry, it is suggested to take an integrated approach, combining multi-product integration such as biodiesel, ethanol and biogas, and exploring coordinated development with industries like livestock and poultry breeding and protein feed, so as to enhance economic and environmental benefits.

Rapeseed straw bioenergy is not only an effective way to reuse agricultural waste, but also can play a role in mitigating climate change, optimizing the energy structure and promoting the green transformation of rural areas. Its diverse energy products and emission reduction advantages make it an important part of the sustainable energy transition. In the future, with technological progress and policy support, its position in the global renewable energy system is expected to be further enhanced.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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