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Exploring the Potential of Rapeseed Biomass for Renewable Energy

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Abstract The study provides a comprehensive overview of the use of rapeseed in renewable energy. Rapeseed is highly adaptable and has a high oil content, making it an important raw material for biodiesel production. In Europe in particular, rapeseed has become a valuable energy crop. The study covers the characteristics of rapeseed cultivation, the extraction and processing of oil, and the performance of rapeseed byproducts (such as rapeseed cake and straw) in different energy fields. These byproducts can be used to produce biofuels, heat and electricity in many ways. The study also introduces the use of artificial intelligence and geographic information systems. These technologies can help predict rapeseed yields and energy output. The results show that if rapeseed is grown on currently unused arable land, the yield of renewable energy is expected to increase significantly. In terms of energy utilization technology, the study mentions several methods, such as pyrolysis, pelleting and biochar production. These technologies can make the use of rapeseed biomass more efficient and reduce pollutant emissions. There are many benefits to using rapeseed biomass. Not only can it reduce dependence on traditional energy sources such as oil, but it also has a positive effect on sustainable agricultural development and environmental protection.
Keywords Rapeseed biomass; Biofuels; Renewable energy; Pyrolysis; Energy sustainability

1 Introduction

Nowadays, the world's population is increasing, industrial development is getting faster and faster, and the demand for energy is rising. However, traditional energy sources such as coal and oil are slowly running out. At the same time, air pollution and greenhouse gas emissions are becoming more and more serious. In order to alleviate these problems, people have begun to pay attention to the use of renewable energy. Many countries have realized that turning to clean energy is a good way to deal with energy crises and climate change (Masarovičová et al., 2009; Abdulvahitoğlu and Kiliç, 2021; Şenocak and Gören, 2021). Among various renewable energy sources, biomass energy is a promising option. It is renewable, widely distributed, and has a relatively small impact on the environment. Therefore, many people believe that it will be an important part of the future energy system (Masarovičová et al., 2009).

Rapeseed is a common oil crop with good adaptability and high oil yield. It is grown in Europe and many other places (Karaosmanoglu et al., 1999; Abdulvahitoğlu and Kiliç, 2021; Suchocki, 2024). Rapeseed not only produces vegetable oil, but also leaves many by-products, such as straw and seed meal. These are important raw materials for developing biomass energy (Karaosmanoglu et al., 1999; Suchocki, 2024). Because rapeseed produces a lot of oil and can provide a variety of biomass resources, it plays an important role in energy crops (Karaosmanoğlu et al., 1999; Karaosmanoglu et al., 1999; Masarovičová et al., 2009; Ciunel and Klugmann-Radziemska, 2014; Suchocki, 2024). Its oil can be used to produce biodiesel, and its by-products can also be used for electricity, heating or other fuels. Studies have found that rapeseed biomass can replace traditional energy in many ways. Its use can help reduce greenhouse gas emissions and make the energy system more sustainable. In general, the development of energy from rapeseed is beneficial to environmental protection and energy conservation (Ciunel and Klugmann-Radziemska, 2014; Abdulvahitoğlu and Kiliç, 2021; Şenocak and Gören, 2021; Malaťák et al., 2024; Suchocki, 2024).

This study aims to gain a comprehensive understanding of the potential of rapeseed as a clean energy resource. We will introduce its planting characteristics, biomass types, common energy conversion methods (such as pressing, combustion and pyrolysis), and its positive impact on the environment and future application opportunities. We hope to clarify what role rapeseed can play in the global energy transition by organizing these research results and new applications. At the same time, we also analyze the challenges it currently faces and provide some references for future technological development and policy making.

2 Composition and Characteristics of Rapeseed Biomass

2.1 Primary components: stalks, leaves, pods, roots, and residual seeds

After rapeseed is harvested, many plant parts are left, which can be used as biomass resources. They mainly include stems, leaves, pods (also known as pod shells), roots and some seeds that have not been fully harvested. Rapeseed straw is generally composed of stems and pod shells. The ratio of these two parts varies depending on the variety and planting method of rapeseed (Wassner et al., 2020). For example, sometimes the mass ratio of stems to pod shells is between 0.8 and 2.2. In addition to these, the remaining seeds and roots can also be used to develop biomass resources (Medvedev et al., 2020).

2.2 Biochemical profile: lignocellulosic content (cellulose, hemicellulose, lignin), moisture, ash, and calorific value

Rapeseed is a lignocellulosic biomass, the main components of which are cellulose, hemicellulose and lignin. The stem has a high cellulose content and a high calorific value of about 17 to 18 MJ/kg, which makes it suitable for use as energy, and the ash content is relatively low, about 6% (Wassner et al., 2020). The composition of the husk is different from that of the stem. The cellulose and lignin content is relatively low, but the ash content is higher, generally between 5% and 14%. Therefore, the husk is more suitable for biochemical processing, such as extracting chemicals. When rapeseed biomass is broken down by enzymes, the composition of lignin and hemicellulose will affect the release of sugars. When the content of components such as G-type lignin, fucose, galactose, arabinose and rhamnose is low, it is more conducive to saccharification and ethanol production (Pei et al., 2016). Rapeseed contains a lot of crude protein and has a high energy value, about 13 MJ/kg, which is higher than the stem and leaf parts (about 9.6 MJ/kg) (Medvedev et al., 2020). In some energy conversion methods, such as pyrolysis or hydrothermal carbonization, the calorific value of rapeseed can be even higher, sometimes reaching 25 MJ/kg, and the water content is not high, making it suitable for energy (Vallejo et al., 2024; Wang et al., 2024).

2.3 Comparative analysis: how rapeseed compares with other common bioenergy crops like corn stover, miscanthus, and switchgrass

Compared with several other common energy crops, such as corn stalks, miscanthus and switchgrass, rapeseed also has many advantages. In terms of calorific value: the calorific value of rapeseed stems is about 17 to 18 MJ/kg, which is similar to corn stalks, miscanthus and switchgrass. If processed, such as hydrothermal carbonization, the calorific value can be increased to 25 MJ/kg, even exceeding some herbaceous crops (Wassner et al., 2020; Vallejo et al., 2024). Ash content: The ash content of rapeseed stems is low, about 6%, which is conducive to direct combustion. The ash content of pods is higher, so be careful to separate them when using them (Wassner et al., 2020). In terms of composition: The ratio of lignin to cellulose in rapeseed is similar to that of corn straw. However, its hemicellulose monosaccharides and lignin types have a special effect on decomposition efficiency (Pei et al., 2016). In terms of yield: The yield of rapeseed straw is between 2 and 6 tons per hectare, which is comparable to crops such as corn. However, the yield will also be affected by the variety and planting method (Wassner et al., 2020).

3 Cultivation Practices and Biomass Yield Optimization

3.1 Agronomic practices: soil requirements, sowing methods, irrigation, and fertilization

To grow rapeseed well, with high yield and good efficiency, we need to start from multiple aspects, such as soil, sowing methods, watering and fertilization. It is important to choose the right tillage method, such as medium-depth tillage. This can improve the soil structure, retain water and nutrients, and keep the temperature suitable. Seedlings are easier to survive the winter and grow faster, which will eventually increase the yield (Wang et al., 2023a). In arid or semi-arid areas, water-saving methods such as ridges and furrows to collect rainwater and mulching are particularly effective. These measures can increase the water storage in the soil, enhance photosynthesis and water use efficiency, and finally increase yields and bring better economic returns (Wang et al., 2023b). The method of irrigation and nitrogen fertilizer application is also critical. Reasonable watering and appropriate nitrogen fertilizer application can make the stems of rapeseed firm, less prone to lodging, and higher yield (Brčić et al., 2023; Guo et al., 2024). In addition, timely weeding and drainage should not be ignored, which can help stabilize and increase yields (Zhang et al., 2020).

3.2 Varietal development: advances in breeding for dual-use (oil + biomass) cultivars

In recent years, the direction of breeding has begun to change. People not only want rapeseed that produces more oil, but also want the kind that can provide more biomass. By improving genotypes and utilizing hybrid advantages, some varieties can not only ensure more grains, but also leave a lot of high-quality straw and pods for use as biomass raw materials (Zheng et al., 2022; Brčić et al., 2023). Different rapeseed varieties respond differently to nitrogen fertilizers. Some grow more vigorously when there is more nitrogen fertilizer, with higher biomass and energy value, and better combustion effect (Brčić et al., 2023). The future breeding goal is to design high-yield and versatile varieties, combining ideal design and hybrid advantage (Zheng et al., 2022).

3.3 Yield influencing factors: climate, plant density, harvesting time

The biomass yield of rapeseed is affected by many factors, mainly climate, planting density and when to harvest. Generally speaking, it is more appropriate to control the density of 25 to 37 plants per square meter when sowing in October, which helps to stabilize and increase yield (Xie et al., 2023). If the density is too small or too dense, there will be problems. It is ideal to control it between 360 000 and 540 000 plants per hectare. This will allow the plant to better distribute nutrients, the canopy structure will be more reasonable, and help improve the efficiency of light energy utilization (Xie et al., 2023; Lin et al., 2024b). A new approach is to mix tall and short stalks. As long as the proportion of tall stalks does not exceed 20%, space and light are better utilized, and the yield increase is also obvious (Lin et al., 2024a). Local weather conditions, such as precipitation and temperature, will also affect the final yield. The time of harvesting should also be chosen early or late, and it is best to adjust management methods according to local conditions (Zhang et al., 2020; Brčić et al., 2023).

4 Conversion Technologies for Energy Production

4.1 Thermochemical processes

4.1.1 Combustion

Byproducts of rapeseed, such as rapeseed cake and pellets, can be burned directly. These biomasses can provide heat and electricity. Studies have found that rapeseed pellets, a byproduct of biodiesel production, can not only feed livestock, but also burn well in boilers. This usage is not only environmentally friendly, but also suitable for daily scenarios such as household water heaters (Ciunel and Klugmann-Radziemska, 2014; Suchocki, 2024). Relevant data show that rapeseed oil and its byproducts are feasible as alternative fuels (Suchocki, 2024).

4.1.2 Pyrolysis

Pyrolysis is an important technology for converting biomass such as rapeseed straw and stems into energy. Slow pyrolysis is generally carried out between 350 ℃ and 650 ℃. At 650 ℃ and a faster heating rate, the most pyrolysis oil can be obtained, which can be used as biofuel (Karaosmanoğlu et al., 1999). If rapeseed residue is pyrolyzed, 35%~40% of biochar can be obtained. These charcoals have a high calorific value (greater than 34 kJ/g) and can be used directly as energy (Güleç et al., 2022a; 2022b) (Figure 1).

4.1.3 Gasification

Although this abstract does not explain in detail how to gasify rapeseed, other studies have said that gasification is another effective thermochemical method. Rapeseed, a lignocellulosic biomass, can also be converted into energy in this way. Gasification can also be combined with other renewable energy technologies to make it more environmentally friendly (Lee et al., 2023; Tshikovhi and Motaung, 2023).

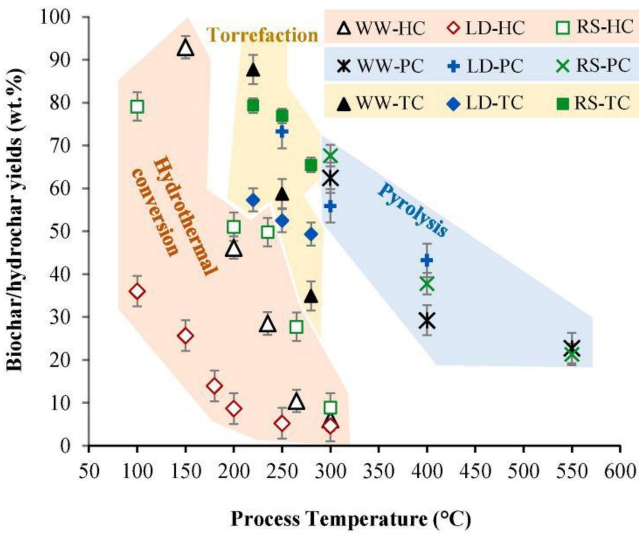

Figure 1 Biochar/hydrochar yields of RS, WW, and LD under the thermal conversion techniques of hydrothermal conversion (HC), pyrolysis (PC), and torrefaction (TC) (Adopted from Güleç et al., 2022a)

4.2 Biochemical processes

4.2.1 Anaerobic digestion

Although there is no experimental data specifically on anaerobic digestion of rapeseed biomass, it is generally believed that agricultural waste such as rapeseed can be used to produce gas (such as biogas) by anaerobic digestion. This method can effectively utilize farmland waste and also contribute to the development of green energy (Zhou et al., 2022; Tshikovhi and Motaung, 2023).

4.2.2 Fermentation

Rapeseed oil can also be converted into biofuels such as biodiesel through fermentation and other methods. Current research focuses on optimizing oil extraction and conversion methods, hoping to improve the yield and quality of biodiesel, which is very helpful for the development of renewable energy (Aslan, 2020; Suchocki, 2024).

4.3 Emerging technologies: hydrothermal liquefaction, torrefaction

4.3.1 Hydrothermal liquefaction

Hydrothermal liquefaction is a relatively new thermal treatment method suitable for processing biomass such as rapeseed. Studies have shown that after hydrothermal reaction of rapeseed residue, about 75% of the product can be obtained. The calorific value of these charcoals is also high, exceeding 30 kJ/g, which is suitable for use as fuel (Güleç et al., 2022a; 2022b). This process is mainly a decarboxylation reaction, which can produce a carbon structure with a high H/C ratio and a low O/C ratio, making the fuel quality better (Güleç et al., 2022b).

4.3.2 Torrefaction

Torrefaction is a mild heat treatment method. The structure and reactivity of the treated rapeseed residue charcoal will be more suitable for use as energy (Güleç et al., 2022a; 2022b).

5 Biofuels from Rapeseed Biomass

5.1 Biodiesel: primarily from rapeseed oil (brief for context)

Rapeseed (*Brassica napus* L.) has a high oil content and is adaptable to various environments. It is widely used in Europe to produce biodiesel. Rapeseed oil can be processed by pressing, solvent extraction and refining. These processes are highly efficient, and the fatty acid methyl ester (FAME) produced is what we call biodiesel. This oil can not only be used directly as a fuel, but can also be mixed with other fuels such as alcohol or hydrogen. It has a good combustion effect and relatively clean emissions (Masarovičová et al., 2009; Aslan, 2020; Suchocki, 2024). In addition, rapeseed meal left after biodiesel production can also be used as fuel (Suchocki, 2024).

5.2 Bioethanol: using lignocellulosic residues

After rapeseed is harvested, stems and straw are left. These are lignocellulosic agricultural wastes that can be used to make bioethanol. As long as they are processed by biochemical methods, they can be converted into ethanol and used to mix with gasoline as fuel. Many studies have found that these residues have great energy potential. If used well, they can not only increase the supply of renewable energy, but also meet the electricity needs of many households (Masarovičová et al., 2009; Şenocak and Gören, 2021).

5.3 Biogas and syngas: through anaerobic and thermochemical processes

Rapeseed biomass can also be used to produce gas in two ways. One is anaerobic digestion, which can produce biogas; the other is thermal treatment technology, such as pyrolysis or gasification, which can produce syngas. Slow pyrolysis of rapeseed stems can not only produce liquid fuel (pyrolysis oil), but also have good yields, making it a potential biofuel (Karaosmanoğlu et al., 1999). Anaerobic digestion of these agricultural wastes can not only turn waste into resources, but also provide clean energy for rural areas (Karaosmanoğlu et al., 1999; Şenocak and Gören, 2021).

5.4 Solid biofuels: pellets and briquettes

Rapeseed meal and straw can also be pressed into pellets or briquettes for use as solid fuel. The pellets can be burned directly and are suitable for use in domestic hot water equipment, etc. Because these pellets are renewable, they are also more environmentally friendly (Ciunel and Klugmann-Radziemska, 2014). Rapeseed straw that has been thermally treated will become biochar. This type of charcoal emits less CO and nitrogen oxides when burned and has a higher combustion efficiency (Malaťák et al., 2024). If some waste rapeseed oil is added, the calorific value of the pellets will be increased and the fuel effect will be better (Gheorghe and Neacsu, 2024).

6 Environmental and Economic Assessment

6.1 Carbon footprint reduction: LCA (life cycle assessment) perspectives

From a life cycle assessment (LCA) perspective, rapeseed biomass performs well in terms of emissions reduction. Many studies have found that biodiesel made from rapeseed oil emits 56% to 74% less greenhouse gases than traditional fossil fuels. Among them, alternative fuels have the most significant emission reduction. Rapeseed still emits a lot of carbon when it is grown, especially when fertilizers are used and intensive cultivation is carried out, which can account for 65% to 100% of total emissions (González-García et al., 2013; Gupta et al., 2022; Yang et al., 2022) (Figure 2). To further reduce emissions, the planting method can be adjusted, such as reducing the amount of fertilizers used, while also using by-products such as glycerol. In some cases, this can reduce carbon emissions by another 14% to 33.6% (Gupta et al., 2022).

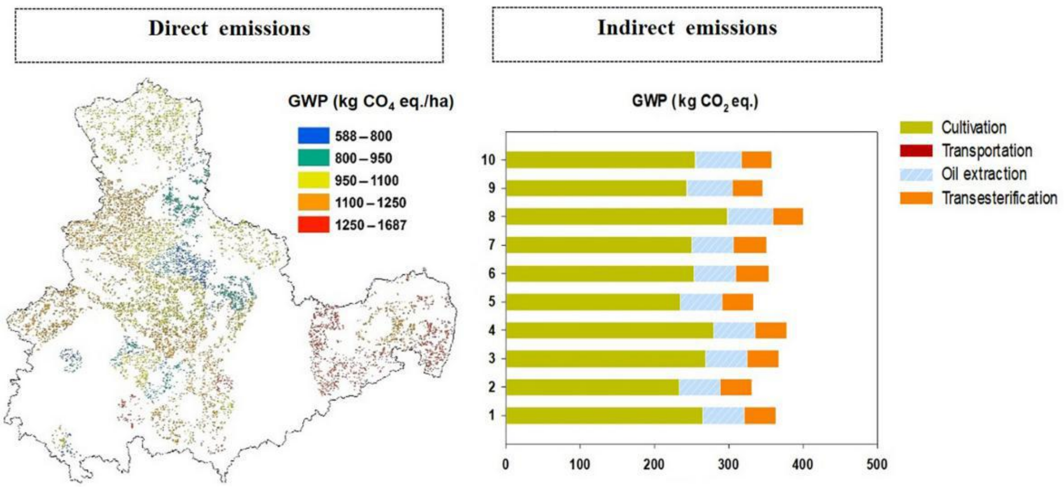

Figure 2 (a) Spatial distribution of global warming potential (GWP) caused by direct emissions from producing one hectare of rapeseed and (b) magnitude of GWP resulting from indirect emissions from producing 1 t of rapeseed for catchments 1-10 (Adopted from Yang et al., 2022)

6.2 Soil and water impacts: residue retention vs. complete biomass removal

Rapeseed leaves residues after harvest, and how these residues are handled will affect soil and water resources. If they are left in the field, they can not only increase soil organic matter, but also prevent soil erosion and make the soil more water-retaining (Esmaeilpour-Troujeni et al., 2021). However, if all the residues are removed, the soil may become poorer and water will be easily lost. Therefore, it is better to retain some of the residues. At the same time, reducing water and pesticides in the production process and using more organic fertilizers can not only increase yields, but also make the entire system more environmentally friendly and sustainable.

6.3 Economic viability: cost-benefit analysis across energy conversion pathways

Whether rapeseed biomass can make money depends on many factors. Studies have shown that the larger the scale of biodiesel production, the lower the cost. However, the cost of growing rapeseed is still the key to determining profitability (Yang et al., 2022). Fortunately, there are by-products in the production process, such as rapeseed meal and pellets, which can be used to feed animals or burn as fuel, making the entire project more cost-effective (Ciunel and Klugmann-Radziemska, 2014; Suchocki, 2024). Whether it is making biodiesel, burning pellets or hybrid power generation, the cost-effectiveness of different methods is different. It should be considered together based on the price of raw materials, the market conditions of the energy market and whether there is policy support (Ciunel and Klugmann-Radziemska, 2014; Jahangir and Cheraghi, 2020).

6.4 Policy frameworks: subsidies, carbon credits, and renewable mandates

The role of policies is very critical. Policy tools such as subsidies, carbon credits, and renewable energy quotas can make projects more profitable and encourage more people to use renewable energy (Bacenetti, 2020; Jahangir and Cheraghi, 2020). Different places have different resources and conditions, and policies must be formulated in accordance with local realities. Using regionalized LCA models for analysis can help find a better balance between environmental protection and economy (Bacenetti, 2020; Yang et al., 2022).

7 Integration with Circular Economy and Agricultural Systems

7.1 Byproduct utilization: biochar, digestate for soil amendment

Rapeseed biomass has many uses in the circular economy. Through pyrolysis technology, agricultural waste such as rapeseed meal can be converted into biochar, gas and bio-oil. The yield of biochar can reach 53%, and it has good stability and strong surface activity. It can improve soil quality and lock carbon when used in the soil (Yrjälä et al., 2022; Gallorini et al., 2023). Rapeseed and byproducts can also produce biogas and digestate through anaerobic fermentation. This digestate can be used as organic fertilizer and returned to the fields, which not only improves soil fertility, but also allows nutrients to circulate and reduces dependence on chemical fertilizers (Haque et al., 2023; Rodríguez-Espinosa et al., 2023; van Selm et al., 2025) (Figure 3). These byproducts are well utilized, which not only reduces the accumulation of agricultural waste, but also promotes the sustainable development of agriculture.

7.2 Crop rotation and residue management: enhancing soil fertility

In circular agriculture, the rotation of rapeseed and other crops, coupled with the proper treatment of straw, is very helpful for soil health. Rapeseed straw is an organic residue that can be used through composting, returning to the field or making biochar. These methods can increase the organic matter in the soil, improve the soil structure, and promote the growth of microorganisms, thereby improving soil fertility and crop yields (Duque-Acevedo et al., 2020; Rodias et al., 2020; Rodríguez-Espinosa et al., 2023; Toplicean and Datcu, 2024). These organic wastes will release nitrogen after decomposition, which can be absorbed by crops, reducing dependence on chemical fertilizers and reducing greenhouse gas emissions (Rodias et al., 2020; Rodríguez-Espinosa et al., 2023). Crop rotation plus straw management can make agriculture more efficient and environmentally friendly, and is a key practice in building a green agricultural system.

7.3 Biorefinery concept: maximizing value from rapeseed through multi-product recovery

The core idea of biorefining is to “eat up” rapeseed biomass as much as possible. For example, rapeseed can be pressed for oil as fuel, and the remaining meal and husk should not be wasted. They can be used to extract protein, feed livestock, or be made into biochar, biogas and fertilizer through pyrolysis and anaerobic digestion (Gallorini et al., 2023; Toplicean and Datcu, 2024; Suchocki, 2024). This multi-path development approach can greatly improve the economic value and environmental benefits of rapeseed, and also reduce the generation of waste (Sherwood, 2020; Toplicean and Datcu, 2024; Suchocki, 2024).

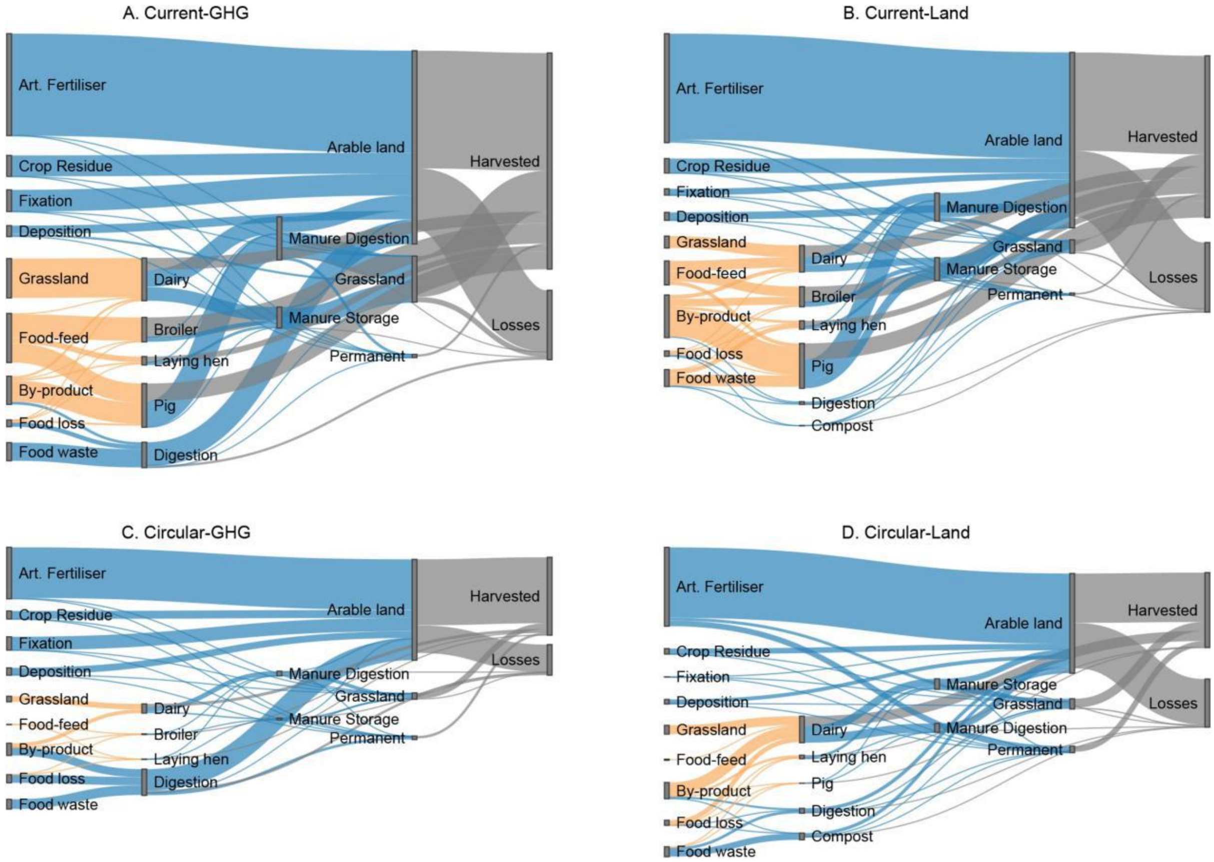

Figure 3 Nitrogen (N) flows through the food system for feed (orange flows) and fertiliser (blue flows). Animal feed (food feed, grassland) is fed to livestock while residual streams are either fed to livestock, composted, or digested. Livestock produce manure which is digested or used as fertiliser on arable land and grassland. Arable land and grassland are also fertilised with compost, digestate, artificial fertiliser and crop residues. N deposition and fixation also contribute to fertilisation. Harvested N includes feed, food and by-products including food losses and waste. Labels refer to vertical grey bars. In this figure GHG emissions from anaerobic digestion are assigned to the energy sector (Adopted from van Selm et al., 2025)

8 Technological and Logistical Challenges

8.1 Feedstock collection and storage

Collecting and storing rapeseed biomass is not easy. Because rapeseed is a seasonal crop and can only be harvested for a period of time a year, the supply of raw materials is not very stable. This requires an efficient logistics system to ensure a continuous supply of raw materials (Bui et al., 2023). Biomass is easily damp and deteriorates during storage, which will lead to reduced energy and poor quality. In order to avoid these problems, special transit warehouses and pre-arranged pre-treatment processes are required. There are generally two ways to collect: one is to collect according to demand, and the other is to collect according to supply. In terms of transportation, multiple methods are also needed, such as road and rail, to improve efficiency.

8.2 Pretreatment requirements: technical constraints in lignocellulose processing

Before materials such as rapeseed straw are turned into energy, they must be processed first. This step is more complicated because lignocellulose is difficult to decompose. Commonly used methods include heat treatment, mechanical treatment, and biological treatment, but they all have some problems, such as high energy consumption, complex equipment, and high cost (Banerjee, 2022; Tshikovhi and Motaung, 2023). How to break the wood structure more efficiently and improve conversion efficiency is still a technical problem. Moreover, these treatment methods are also limited in large-scale commercial applications, not only because of technical difficulties, but also because of high costs.

8.3 Infrastructure needs: transport, centralized processing plants

In order to use rapeseed biomass for power generation or heating, infrastructure must keep up. The first is the transportation problem. These biomasses are large in size and low in calorific value, so the cost of transportation is particularly high (Bui et al., 2023). Then there is the processing plant. Building a centralized processing plant can improve efficiency and reduce waste, but it also requires a stable supply of raw materials, and the logistics system must be in place (Gupta et al., 2022). If these infrastructures are not up to date, the development of biomass energy will be slowed down (Gupta et al., 2022; Bui et al., 2023).

8.4 Economic bottlenecks: capital cost, scale-up barriers

The investment in rapeseed biomass energy projects is not small. The equipment is expensive, the operating costs are high, and the technology is not mature enough. The infrastructure in many places is not perfect. If you want to carry out large-scale production, you have to face various economic pressures such as unstable raw material sources, expensive transportation, and difficult pretreatment (Banerjee, 2022; Gupta et al., 2022; Tshikovhi and Motaung, 2023). These problems make it difficult to promote. If you want to solve them, you have to rely on policy support and technology upgrades to promote them together (Abdul Malek et al., 2020; Gupta et al., 2022; Tshikovhi and Motaung, 2023).

9 Case Study: Rapeseed Biomass for Energy in Germany

9.1 Overview: Germany's dual-use rapeseed initiative (e.g., biodiesel + biogas from residues)

Germany is a major rapeseed grower and user in Europe. Rapeseed here is not only used to produce biodiesel, but the remaining by-products, such as rapeseed cake and straw, are also developed to produce biogas. This practice of "producing both oil and energy" is called the "dual utilization" model. This model makes the utilization rate of rapeseed higher, not only promoting the development of renewable energy, but also allowing the two industries of agriculture and energy to achieve win-win cooperation (Woźniak et al., 2019; Suchocki, 2024).

9.2 System design: farm-scale and cooperative biogas units

In Germany, the energy utilization of rapeseed biomass is often operated on a farm or cooperative basis. Farmers or cooperatives centrally process the residues of rapeseed and produce biogas through anaerobic fermentation. These gases can be used directly locally or connected to the power grid and sold. This distributed small-scale system can reduce transportation costs, increase energy self-sufficiency, and also drive the development of the rural economy (Yang et al., 2022; Suchocki, 2024).

9.3 Outcomes: energy output, emissions saved, local income generation

Germany's rapeseed biomass system has achieved many results. For example, biodiesel emissions are about 56% to 71% lower than traditional fossil fuels, and the carbon reduction effect is obvious (Yang et al., 2022). At the same time, the production of biogas and biodiesel has also increased farmers' income, provided employment opportunities, and enhanced rural economic vitality (Woźniak et al., 2019; Yang et al., 2022; Suchocki, 2024).

9.4 Challenges encountered: weather variability, subsidy dependency

Although the results are good, the German system has also encountered some problems. For example, climate change brings many risks. The severe drought in 2018 caused a significant reduction in rapeseed production, insufficient raw materials, and affected the production of biodiesel (Yang et al., 2022; Sadr et al., 2024). Many of these energy projects rely on policy subsidies to maintain. Once the subsidies change or are cancelled, the investment will become more unstable and affect normal operations (Woźniak et al., 2019; Yang et al., 2022).

9.5 Lessons learned: policy stability, farmer engagement, co-product value

Germany's experience tells us that if we want rapeseed biomass energy projects to develop for a long time, policies must be stable (Yang et al., 2022; Sadr et al., 2024). Farmers' participation is also critical. Through cooperatives, everyone works together, which is more efficient and has better economic benefits. We should not only focus on rapeseed oil, but also make full use of by-products, such as rapeseed cake and straw, and turn them into energy or useful products, so as to truly enhance the competitiveness and sustainability of the entire industry (Woźniak et al., 2019; Yang et al., 2022; Suchocki, 2024).

10 Conclusion and Future Perspectives

Rapeseed is a promising renewable energy crop. With its high oil content and strong adaptability, it can be used to produce biodiesel and other biofuels. In Europe and other regions, rapeseed has become an important energy crop. In addition to oil extraction, rapeseed byproducts are also useful. Straw, rapeseed meal and pressed pellets can not only be used as biofuels, but also be used to feed livestock or as an alternative energy source for home heating. This can make better use of resources. Studies have also found that planting rapeseed on previously idle arable land and then using its waste can greatly increase local energy output and meet the clean electricity needs of many households. The combination of artificial intelligence and geographic information systems has also helped to find the most suitable places for planting. Rapeseed biomass has new uses, such as high-performance supercapacitor materials, opening up new directions in the field of new energy.

Although rapeseed biomass has a good prospect, there are still many problems to be solved. First, the varieties of rapeseed need to be improved. In order to make it more productive and disease-resistant and drought-resistant, genetic breeding work must continue. Some materials used in the process of making biofuels, such as enzymes, are too expensive. This limits its large-scale promotion. Now we urgently need to find cheaper and more effective enzymes and improve the extraction methods. Another problem is that how to integrate rapeseed energy in different regions and how to use it in multiple ways is not yet mature. There is a lack of a complete set of systematic models, and there is no complete life cycle assessment tool to judge how sustainable it is.

In the future, the development of rapeseed biomass energy can be carried out in several directions. First, it is necessary to consider the combination of ecology and economy in planting planning, so that agriculture, energy and environmental protection can develop together. Second, more policy support is needed, and specific regulations and incentives are introduced to promote the wider use of rapeseed energy. Third, we must strengthen international cooperation and do more scientific research exchanges. Including variety improvement, production process innovation, industrial chain integration and other aspects, only when the world promotes it together can the competitiveness of rapeseed biomass energy be truly improved.

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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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