

Research Article

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Characterization of Rapeseed Oil for Biodiesel Production: A Comparative Study

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Abstract This research mainly compares several aspects of rapeseed oil as a raw material for biodiesel. This includes its physical and chemical properties, production process, fuel performance, environmental impact and industrial applications. Different catalysts, process parameters and conversion methods were compared in the study. It was found that when rapeseed oil was used to make biodiesel, the yield was good and the fuel performance was also excellent. For instance, the cetane number, calorific value and low-temperature fluidity can all meet the standards. The emission performance also complies with international fuel requirements. Rapeseed oil biodiesel is of great significance in reducing greenhouse gas emissions and achieving renewable energy goals. However, many problems were also encountered during the promotion process. For instance, high raw material costs, conflicts in land use, competition with food applications, and how to make high-value use of by-products. Current new research is paying more attention to green catalysts, enzymatic processes, the reuse of by-product glycerol, and the integration with the circular bioeconomy. In the future, genetic breeding, process integration and policy support may further enhance the sustainability and market competitiveness of this biodiesel. The purpose of this research is to provide references and directions for energy policies, industrial development and subsequent scientific research.

Keywords Rapeseed oil; Biodiesel; Fuel performance; Life cycle assessment; Sustainable development

1 Introduction

The global energy crisis is becoming increasingly severe, and the reserves of fossil fuels are also constantly decreasing. This has led countries to actively seek new sustainable energy sources. The excessive use of fossil fuels not only brings about energy security problems, but also aggravates environmental pollution and greenhouse gas emissions (Gupta et al., 2022; Makarevi Cienet al., 2024). Therefore, the development and utilization of renewable energy have become the key methods to solve the energy crisis and reduce carbon emissions. Biodiesel is a renewable fuel that can be naturally degraded and is also relatively environmentally friendly. It can reduce greenhouse gas emissions and lower reliance on oil, and thus has received widespread attention. Biodiesel is mainly produced through transesterification reactions of vegetable oils or animal fats. Its combustion performance and physicochemical properties are similar to those of ordinary diesel and can be directly used in existing diesel engines (Santaraite et al., 2020; Sendžikienė et al., 2020; Gupta et al., 2022).

Among many raw materials, rapeseed oil has a significant advantage. It has a high oil content, approximately 40%, and a large global output. Moreover, its fatty acid composition is suitable for use as fuel. Therefore, rapeseed oil has become one of the commonly used raw materials for biodiesel in Europe and worldwide (Azcan and Danisman, 2008; Santaraite et al., 2020; Abdulvahitoglu and Kilic, 2021). Rapeseed oil not only has a high yield, but its fatty acid composition is also beneficial. The contents of oleic acid, linoleic acid and alpha-linolenic acid are all abundant. These components can improve fuel performance and are also beneficial to oxidation stability (Khan et al., 2023). Biodiesel made from rapeseed oil not only meets international standards such as ASTM and EN, but also performs well in terms of environmental and economic benefits (Rashid and Anwar, 2008; Rezki et al., 2020).

In recent years, researchers have been improving the production methods of rapeseed oil biodiesel. This includes choosing the appropriate catalyst, optimizing reaction conditions, and assessing its impact on the environment. These studies have promoted the industrialization process of rapeseed oil biodiesel. The objective of this review is to sort out and compare the raw material characteristics, process conditions, catalytic systems and fuel performance of rapeseed oil in biodiesel production. It also combines the latest research cases to explore the advantages and difficulties under different process paths. Through these analyses, it is hoped that references can be provided for optimizing production processes, improving fuel quality and promoting sustainable development.

2 Biodiesel Production Pathways

2.1 Overview of common feedstocks: vegetable oils, animal fats, waste oils

There are three main raw materials for biodiesel: vegetable oil, animal fat and waste oil. Common vegetable oils include rapeseed oil, soybean oil and sunflower oil. Waste oils include waste cooking oil and food waste oil (Encinar et al., 2020; Santaraite et al., 2020; Szkudlarek et al., 2024). In Europe, rapeseed oil is widely used as a raw material for biodiesel due to its high oil content and suitable fatty acid composition (Encinar et al., 2020; Santaraite et al., 2020). In recent years, due to the increasingly fierce competition in food and fuel, low-quality rapeseed oil and waste oil have also drawn attention. This type of raw material is cheaper and can also reduce the contradiction with food (Sendikien et al., 2022).

2.2 Transesterification process and key chemical reactions

Biodiesel is mainly produced through transesterification reactions. During this process, triglycerides in vegetable oil or animal fat react with methanol or ethanol in the presence of a catalyst to form fatty acid esters (that is, biodiesel) and glycerol (Rashid and Anwar, 2008; Georgogianni et al., 2009; Szkudlarek et al., 2024). Commonly used catalysts include base catalysts (NaOH, KOH), acid catalysts, solid base catalysts (CaO, MgO, etc.), and enzyme catalysts (Essamlali et al., 2019; Santaraite et al., 2020; Lazdovieca et al., 2023). The basic equation of the reaction is as follows:



2.3 Factors influencing biodiesel yield and quality

The yield and quality of biodiesel are influenced by many factors.

Types and dosages of alcohols: Methanol is the most common, with a fast reaction speed and a low price. Ethanol is more environmentally friendly, but the yield may be slightly lower (Khan et al., 2023; Szkudlarek et al., 2024; Ferreira et al., 2025). The common molar ratio of alcohol to oil is 6:1 to 15:1. Too high or too low will affect the yield and the generation of by-products (Rashid and Anwar, 2008; Lazdovieca et al., 2023).

Catalyst types and concentrations: Alkaline catalysts (NaOH, KOH) react quickly, but have high requirements for raw materials. Solid base catalysts (CaO, MgO) are easy to separate and reuse, and are more environmentally friendly (Rashid and Anwar, 2008; Georgogianni et al., 2009; Essamlali et al., 2019; Lazdovieca et al., 2023; Szkudlarek et al., 2024). Enzyme catalysts are suitable for raw materials with high free fatty acids. They are environmentally friendly but costly (Li et al., 2006; Jeong and Park, 2008; Santaraite et al., 2020).

Reaction conditions: Temperature, stirring and time will all affect the result. The general optimal temperature is 50 °C~65 °C. The stirring and time should be adjusted according to the catalyst and raw materials (Azcan and Danisman, 2008; Rashid and Anwar, 2008; Khan et al., 2023; Lazdovieca et al., 2023).

The quality of raw oil: If the content of free fatty acids in the raw oil is high, saponification reaction is likely to occur, resulting in a decrease in yield. This problem can be solved by enzymatic catalysis or two-step method (Li et al., 2006; Santaraite et al., 2020; Send and ikien et al., 2022).

3 Physicochemical Properties of Rapeseed Oil

3.1 Fatty acid profile (oleic, linoleic, linolenic content)

Rapeseed oil is rich in unsaturated fatty acids, accounting for approximately 93%. Among them, oleic acid (C18:1) is the most abundant, followed by linoleic acid (C18:2) and alpha-linolenic acid (C18:3). The content of saturated

fatty acids is relatively low, approximately 7% (Nath et al., 2016; Nje et al., 2023). Through breeding and genetic engineering, researchers have developed different types of rapeseed oil, such as high oleic acid type (oleic acid up to 86%) and high erucic acid type (erucic acid up to 78%), which can meet the needs of industrial use and biodiesel production.

3.2 Key quality parameters: viscosity, density, iodine value, saponification value

Rapeseed oil and biodiesel produced from it can generally meet international standards (EN14214, ASTM D-6751) (Rashid and Anwar, 2008; Essamlali et al., 2017; Rezki et al., 2020). In terms of parameters, the kinematic viscosity of rapeseed oil biodiesel is usually between 4.0 and 5.0 mm²/s (at 40 °C), meeting the standards (Shapovalov et al., 2025). Its density is 0.88~0.90 g/cm³ (at 15 °C), which is similar to mineral diesel. The iodine value reflects the unsaturation of oil products. The iodine value of rapeseed oil biodiesel is generally between 110 and 120 g I₂/100 g, which is higher than that of palm oil and soybean oil (Rashid and Anwar, 2008; Nath et al., 2016). The saponification value is usually between 190 and 195 mg KOH/g, which indicates that it is very suitable for ester exchange reactions.

3.3 Oxidative stability and implications for storage and engine performance

Due to the high proportion of unsaturated fatty acids, the oxidation stability of rapeseed oil biodiesel is relatively poor. It is prone to oxidation during storage, which will increase the acid value, increase the viscosity and form precipitates (Rashid and Anwar, 2008; Khan et al., 2023). If the stability is insufficient, it may affect the long-term use of the engine. However, this problem can be improved by adding antioxidants or increasing the proportion of oleic acid.

4 Fuel Properties of Rapeseed Oil Biodiesel

4.1 Cetane number, calorific value, pour point, cloud point, flash point

The cetane number of rapeseed oil biodiesel (RME) is generally between 51 and 54, which is slightly higher than that of diesel, which is beneficial for engine ignition and combustion (Karaosmanoglu et al., 1997; Rashid and Anwar, 2008). Its high calorific value is slightly lower than that of mineral diesel, approximately 37~40 MJ/kg, but it can still meet the energy requirements of the engine (Ong'era et al., 2023). However, its freezing point and cloud point are relatively high, and its fluidity at low temperatures is worse than that of diesel. Additives need to be added or it needs to be mixed with diesel to improve (Rashid and Anwar, 2008; Stiemieck et al., 2010; Brock et al., 2018). Its flash point is usually greater than 120°C, higher than that of diesel, so the fuel is safer.

4.2 Emission characteristics compared with diesel and other biodiesels

When rapeseed oil biodiesel is used in the engine, CO and particulate matter (PM) emissions can be reduced by up to 60%, but NO_x and CO₂ emissions are slightly higher than those of diesel (Buyukkaya, 2010; Aldhaidhawi et al., 2017). Compared with biodiesel such as soybean oil and palm oil, its emission performance is roughly similar. However, due to the high proportion of unsaturated fatty acids, NO_x emissions are slightly higher. If hydrogen or nano-additives are added during combustion, the emissions of CO and HC can be further reduced, but NO_x still needs to be controlled through post-treatment (Brock et al., 2018; Thiagarajan et al., 2024; Gulcan et al., 2025).

4.3 Engine performance outcomes from literature studies

Many studies have shown that the power of rapeseed oil, biodiesel and their blended fuels in engines is similar to that of diesel. The fuel consumption rate is slightly higher than that of diesel, approximately 8%~11% more, and the thermal efficiency is also slightly lower (Buyukkaya, 2010; Latypov et al., 2021; Zapevalov et al., 2021). The ignition delay time is shortened, the combustion is more stable, but the exhaust temperature will increase slightly. The study also found that the addition of nanoparticles (such as TiO₂, CeO₂) can improve energy utilization efficiency and heat release efficiency, and also reduce costs, but the environmental impact still needs to be further evaluated (Gulcan et al., 2025).

4.4 Regional differences in rapeseed oil biodiesel performance

In Europe, rapeseed oil is the main raw material for biodiesel. It has good fuel performance and emission performance, so it is widely used in the transportation field (Aldhaidhawi et al., 2017; Konur, 2021). In Asia and North America, due to differences in climate, raw material supply and policies, the promotion situation and performance also vary. For example, in low-temperature areas, special attention needs to be paid to the improvement of fuel fluidity (Stiemicek et al., 2010; Brock et al., 2018). In China and Canada, the application of rapeseed oil biodiesel is gradually increasing, and local standards and technologies are also constantly improving (Latypov et al., 2021).

5 Comparative Study Framework

5.1 Criteria for comparison: yield, production cost, lifecycle emissions, environmental impact

In research, several core criteria are often used to compare rapeseed oil biodiesel. First is the yield. Under optimized transesterification conditions, the yield of rapeseed oil biodiesel can exceed 99%, which is higher than that of sunflower oil and waste oil (Solis et al., 2017; Rezki et al., 2020; Khan et al., 2023; Makarevieciene et al., 2023) (Figure 1). The yield is affected by the type of catalyst, alcohol-oil ratio and reaction time. The second is the production cost. The use of solid base, enzyme or carbon-based catalysts, along with process improvements such as continuous reactors and nano-catalysts, can help reduce costs (Hasannia et al., 2024; Gulcan et al., 2025). However, compared with low-cost raw materials such as waste oil, the raw material cost of rapeseed oil is still relatively high (Rezki et al., 2020). In terms of emissions, rapeseed oil biodiesel can significantly reduce CO and PM when burned, but NO_x and CO₂ are slightly higher than diesel (Buyukkaya, 2010; Kumar et al., 2024). From the perspective of life cycle assessment, the planting process, the use of chemical fertilizers and oil extraction all have a significant impact on the carbon footprint (Mikulski et al., 2020; Lovasz et al., 2023; Nasrollahzadeh et al., 2023). As for environmental impacts, reasonable fertilization and irrigation management can increase yields and also reduce environmental burdens. The treatment of by-products during the production process, such as the utilization of glycerol and catalyst recovery, can also affect the overall environmental friendliness.

5.2 Strengths and limitations of rapeseed oil relative to alternatives

The advantages of rapeseed oil biodiesel are its high oil yield, appropriate fatty acid composition and good fuel quality. However, its raw material cost is relatively high, it requires a large amount of cultivated land, its NO_x emissions are slightly higher, and its low-temperature fluidity is also average. Overall, rapeseed oil biodiesel is better than soybean oil and sunflower oil in terms of yield, fuel performance and oxidation stability, but inferior to palm oil and some waste oils in terms of raw material cost and low-temperature performance (Buyukkaya, 2010; Rezki et al., 2020; Khan et al., 2023; Kumar et al., 2024).

5.3 Current trends in breeding and genetic modification for oil quality improvement

At present, there are mainly several directions for improving the quality of rapeseed oil. One is to cultivate varieties with high oleic acid and low erucic acid, which can improve the stability and performance of the fuel. The common methods are traditional breeding and molecular marker techniques (Lovasz et al., 2023; Nasrollahzadeh et al., 2023). Another direction is to enhance stress resistance and high yield, such as by using root-promoting bacteria, organic fertilizers or water-saving irrigation to increase yield and oil quality, while reducing the use of chemical fertilizers to achieve more sustainable production. And then there is genetic engineering. Regulating the synthetic pathway of fatty acids through gene editing can further optimize the composition of oils and fats, making them more suitable for biodiesel production.

6 Case Study: Rapeseed Oil Biodiesel in Practice

6.1 Context: select a country or region with large rapeseed production (e.g., Germany, China, Canada)

Germany is one of the countries with the highest rapeseed production in the world. Rapeseed oil accounts for approximately 80% of the biofuel market in Europe (Gupta et al., 2022). The abundant rapeseed resources provide a reliable raw material base for Germany's biodiesel industry (Konur, 2021; Gupta et al., 2022).

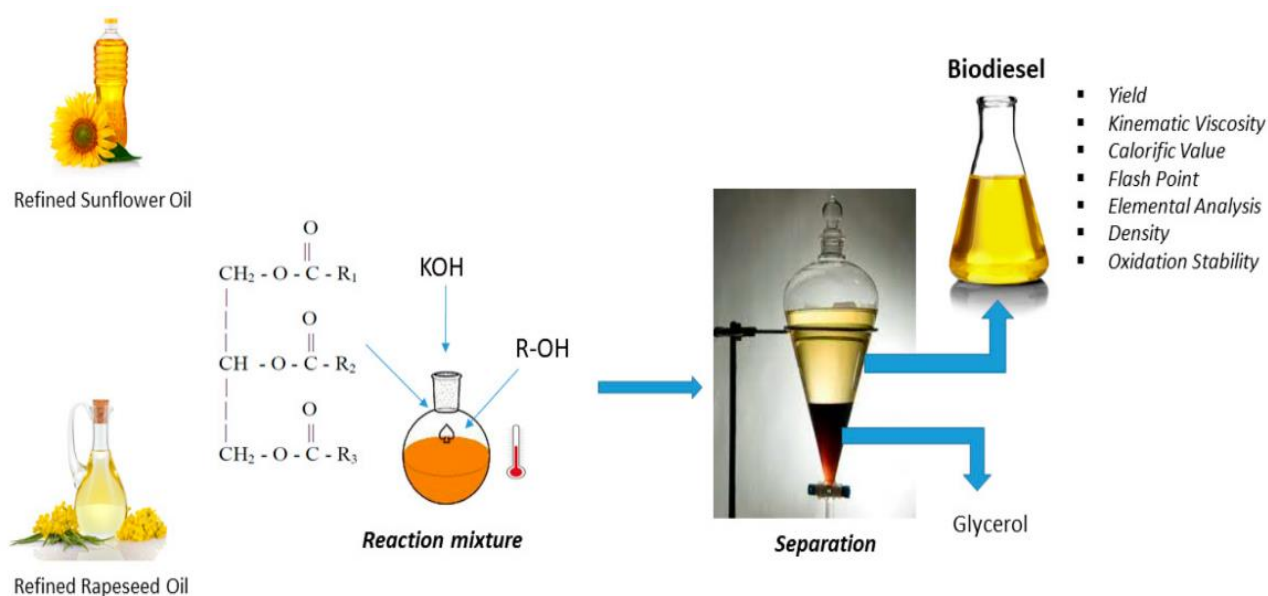


Figure 1 Schematic illustration of the biodiesel production process by transesterification and the parameters for the process and biodiesel characterization. KOH (potassium oxide); R-OH (alcohol) (Adopted from Khan et al., 2023)

6.2 Implementation: overview of local biodiesel industry and use of rapeseed oil as primary feedstock

The biodiesel industry in Germany is very mature, and rapeseed oil is the main raw material. The production process is mainly based on alkali-catalyzed ester exchange. Under optimized conditions (such as a methanol/oil molar ratio of 6:1, KOH concentration of 1.0%, and temperature of 65 °C), the yield can reach 95%~96%, and the products comply with the EU EN and the US ASTM standards (Rashid and Anwar, 2008; Khan et al., 2023). In recent years, there has been an increasing amount of research on green diesel. This type of fuel is obtained through catalytic deoxidation and has better compatibility and storage stability (Stiemcek et al., 2009; 2010; Di Vito Nolfi et al., 2025).

6.3 Findings: production scale, policy support, cost-effectiveness, adoption challenges

In terms of production scale, Germany has both large centralized factories and small local production sites. Greenhouse gas emissions (GWP) from large-scale factories are approximately 2.63 tCO₂-eq/t of biodiesel, while those from small-scale factories are 2.88 tCO₂-eq/t (Gupta et al., 2022) (Figure 2). In terms of policies, the governments of the European Union and Germany have promoted the development of the biodiesel industry through measures such as the Renewable Energy Directive, and set targets and provided subsidies (Konur, 2021). Economic analysis shows that for a factory with an annual output of 50, 000 tons, the return on investment can reach 79.5%, and the unit cost can be reduced to \$722~\$945 per ton (Santaraite et al., 2020). However, there are also some challenges, such as competing with the food industry for raw materials, environmental pressure caused by the use of nitrogen fertilizers, high production energy consumption, poor fluidity at low temperatures, etc. (Stiima Cek et al., 2010; Lovasz et al., 2023).

6.4 Impact: contribution to renewable energy targets, reduction in emissions, socio-economic benefits

The promotion of rapeseed biodiesel has significantly increased the proportion of renewable energy in the transportation sector in Germany, contributing to the EU's goal of reducing greenhouse gas emissions by 55% by 2030 (Makarevi Cienet al., 2024). Compared with mineral diesel, biodiesel has lower carbon emissions throughout its life cycle, with the agricultural stage accounting for more than 65% of the total emissions. Emissions can be further reduced by 14%~33% through optimizing planting methods and by-product utilization (Gupta et al., 2022). In addition, the biodiesel industry can also increase agricultural income, promote rural employment and enhance energy security, but food safety also needs to be taken into account (Santaraite et al., 2020; Lovasz et al., 2023).

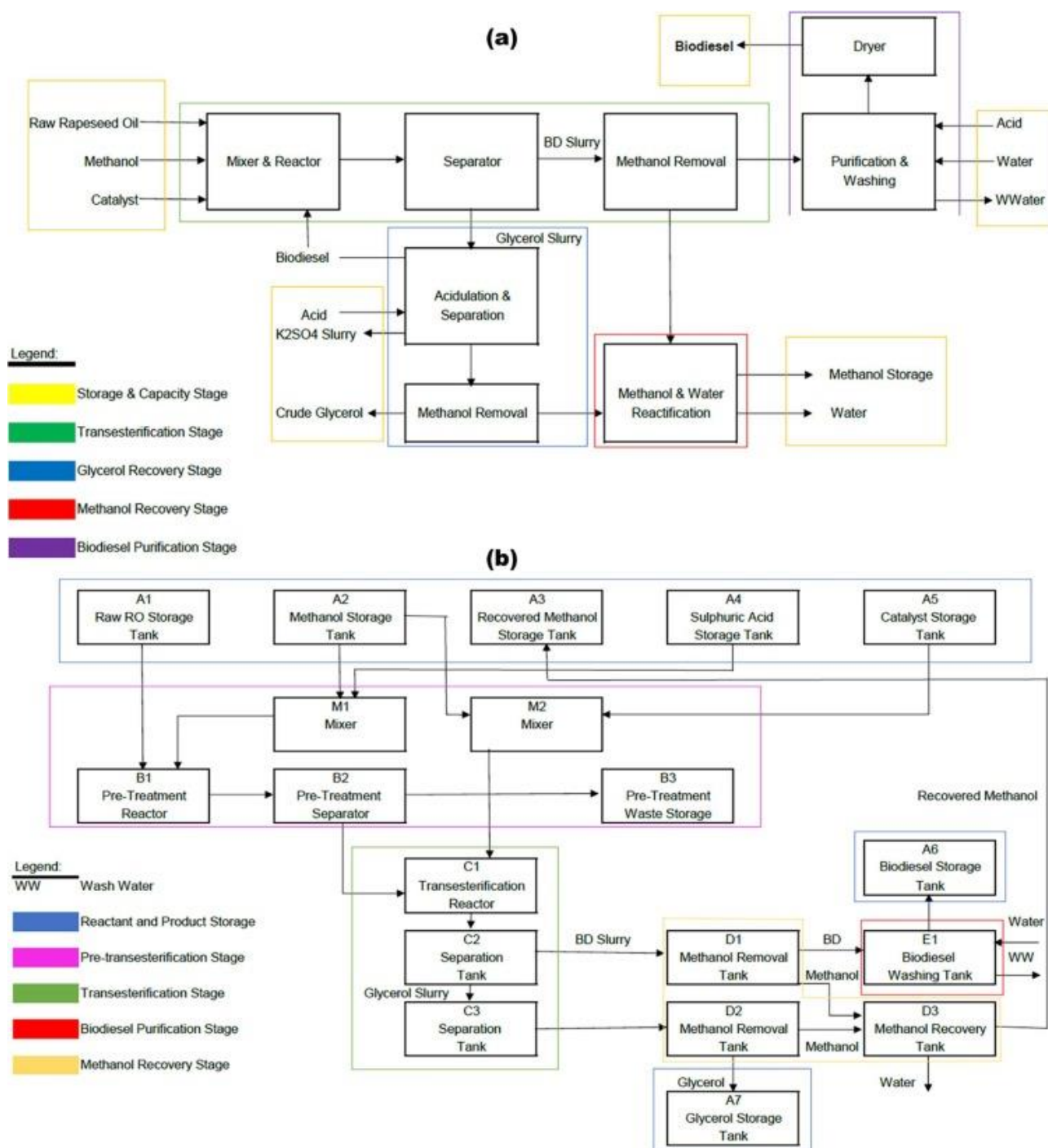


Figure 2 Process flow for (a) plug flow biodiesel reactor used by large-scale and (b) semi-continuous batch biodiesel reactor used by the small-scale biodiesel production schemes (Adopted from Gupta et al., 2022)

6.5 Lessons learned and potential for replication in other regions

From the experience of Germany, high-yield and efficient rapeseed cultivation, policy incentives, process optimization and the utilization of by-products are the keys to the success of the industry. But at the same time, attention should also be paid to the environmental impact and the relationship with the food industry should be well coordinated (Santaraitė et al., 2020; Gupta et al., 2022; Lovasz et al., 2023). This model can be replicated in countries rich in rapeseed resources and with strong policy support, such as China and Canada. However, the specific practices need to be adjusted in combination with local agricultural conditions, energy structure and market demand (Konur, 2021).

7 Challenges and Future Prospects

7.1 Agronomic and environmental challenges (land use, fertilizer input, GHG emissions)

The environmental problems of rapeseed oil biodiesel mainly occur in the planting stage. Land use change, the input of chemical fertilizers, especially nitrogen fertilizers, and irrigation demands are all important sources of greenhouse gas emissions. Emissions at this stage account for more than 65% of the entire life cycle (Gupta et al., 2022). Extreme weather, such as drought, can cause unstable production and increase economic and environmental risks (Yang et al., 2021). If bio-fertilizers (PGPR) and organic fertilizers are used, the amount of chemical fertilizers can be reduced, while increasing production and oil quality, and it is also more in line with the goal of sustainable production (Nasrollahzadeh et al., 2023).

7.2 Competing uses of rapeseed oil (food vs. fuel)

Rapeseed oil can not only be used as edible oil but also serves as an important raw material for biodiesel. As the demand for biodiesel rises, the competition between food and fuel is becoming increasingly prominent. This will push up the prices of raw materials and may also affect food safety (Santaraite et al., 2020). In Europe, more than 70% of rapeseed oil is used to produce biodiesel, which has a significant impact on the food market (Nath et al., 2016).

7.3 Advances in process optimization and co-products (e.g., glycerol valorization)

Researchers are experimenting with new catalysts, such as carbon-based, solid base and enzyme catalysts, and are also developing new process methods, such as enzymatic in-situ transesterification, green solvents and nanocatalysts. These improvements can increase yield, reduce energy consumption and production costs (Santaraite et al., 2020; Babadi et al., 2022; Khan et al., 2023; Hasannia et al., 2024). Glycerol, a by-product in production, can also be utilized, such as as animal feed, chemical raw materials, or as a substrate for fermentation to produce biogas. These methods can enhance economic and environmental value. However, the market for glycerol is not large and its economic value is limited. There is still controversy over how to allocate by-products in the assessment (Yang et al., 2021).

7.4 Integration with circular bioeconomy approaches

The rapeseed oil biodiesel industry is developing towards a circular bioeconomy, with increasing emphasis on by-product reuse, waste recycling and energy diversification (Yang et al., 2021). For instance, rapeseed cake can be used as feed or for biomass energy, and glycerol can be utilized to produce biogas. All these can promote the coordinated development of agriculture, energy and the environment (Suchocki, 2024).

7.5 Outlook on next-generation rapeseed-based biodiesel

One of the future development directions is new fuels such as green diesel (HVO). This type of fuel has a higher calorific value, better chemical stability, and is well compatible with petro-diesel. It is an important trend in the deep processing of rapeseed oil (Stiemicek et al., 2009; Ershov et al., 2022; Di Vito Nolfi et al., 2025). Gene editing technologies (such as CRISPR) and molecular breeding will also continue to increase the yield and quality of oils, cultivate new varieties with high oleic acid and high stress resistance, and promote the development of low-carbon agriculture and clean energy (Nath et al., 2016; Ali and Zhang, 2023). Meanwhile, process integration, raw material diversification and policy support will further promote the global promotion and sustainable expansion of rapeseed oil biodiesel (Yang et al., 2021; Babadi et al., 2022; Suchocki, 2024).

8 Conclusion

Rapeseed oil holds an important position in the global biodiesel industry due to its high oil content, appropriate fatty acid composition and strong adaptability. Many comparative studies have shown that rapeseed oil biodiesel has obvious advantages in fuel performance, environmental benefits and process optimization, but it also encounters problems such as high raw material costs, tight land use and competition for food applications.

In terms of fuel performance, the cetane number, viscosity, density and calorific value of rapeseed oil biodiesel all meet the ASTM and EN standards. Its combustion performance is close to that of mineral diesel, and sometimes

even better. In terms of yield, if the conditions of the transesterification reaction are optimized, such as adjusting the alcohol-oil ratio, catalyst type and reaction temperature, the yield can reach 95%~99%, and it is suitable for different catalysts and process routes. In terms of the environment and economy, life cycle assessment shows that rapeseed oil biodiesel can reduce greenhouse gas emissions by 56% to 71%. However, its economic viability is largely influenced by raw material prices and production scale. The utilization of by-products, such as glycerol and rapeseed cake, can enhance overall economic and environmental benefits and also contribute to the development of a circular bioeconomy. In regions such as Europe, rapeseed oil is the main raw material for biodiesel, accounting for over 80% of the market. It not only becomes an important support for achieving renewable energy goals and reducing emissions in transportation due to its high oil production rate and good fuel properties, but also drives agricultural income growth and rural economic development.

In terms of policy, more attention should be paid to sustainable planting, land use optimization and by-product utilization to reduce competition in food and fuel. In terms of industrial promotion, costs can be reduced through large-scale and intensive production, while promoting technological innovation and high-value utilization of by-products, thereby enhancing economic efficiency and environmental friendliness. Future research can focus on low-carbon planting, green catalysts, non-grain raw materials and new types of biodiesel (such as green diesel and enzymatic processes), promoting the development of rapeseed oil biodiesel towards a more efficient, low-carbon and sustainable direction.

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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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