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Optimizing Rapeseed Oil Yield for Sustainable Biodiesel Production

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Abstract Rapeseed oil is a potential renewable energy source and plays an important role in the development of sustainable fuels. Improving the efficiency of biodiesel production is most important to increase rapeseed oil yield. This study hopes to find ways to increase rapeseed oil yield and biodiesel production efficiency. In our study, we compared the effects of rainwater planting and irrigation planting of rapeseed, and found that when the use of irrigation water, electricity and fungicides is reduced, and the use of certain fertilizers and diesel is increased, the rapeseed yield can be increased by 24.55%. This study analyzed and compared different fertilization methods. The use of high doses of compound fertilizers can not only increase the yield of rapeseed oil, but also increase the final biodiesel yield. Moreover, the quality of biodiesel produced by refined rapeseed oil can meet European standards. The article analyzed various factors that may affect the final yield of biodiesel, including genetic and environmental factors. The result is that the higher the efficiency of photosynthesis, the higher the yield of rapeseed oil. In order to improve the yield and quality of biodiesel, the researchers used a variety of technologies, including ultrasound-assisted and base-catalyzed transesterification. When these technologies are used under ideal conditions, the yield of biodiesel can reach 97.5%.
Keywords Rapeseed oil; Biodiesel production; Exergy analysis; Fertilization systems; Transesterification optimization

1 Introduction

Rapeseed (*Brassica napus*) is a globally important energy crop due to its high oil content and low cost of cultivation. Rapeseed is grown in many parts of the world for edible oil, animal feed, and biodiesel production (Abbadi and Leckband, 2011; Xiong et al., 2022). The cultivar “00” (also known as “canola” or “rapeseed oil”) has important uses in both food and non-food applications, such as biofuels (Abbadi and Leckband, 2011). In some places with suitable climates, such as Iran, improved varieties, such as TERI (OE) R-983, have shown good performance in biodiesel production (Almasi et al., 2019). Rapeseed has a high oil yield and good quality, making it an ideal feedstock for biodiesel, a clean energy source produced from renewable feedstocks. The production and combustion process of biodiesel has less adverse impact on the environment and is an excellent alternative to fossil fuels (Lovasz et al., 2023; Tanner et al., 2023).

The key to enhancing the sustainability of biodiesel is to increase the yield of rapeseed. The higher the oil content of rapeseed, the more efficient it is in producing biodiesel. Large-scale production and use of biodiesel can reduce dependence on pesticides, fertilizers, water, etc., and reduce environmental pollution. Rashid and Anwar (2008) and Santaraite et al. (2020) successfully improved the oil yield of rapeseed and the quality of biodiesel by adjusting fertilization methods, reaction conditions and processing methods. In 2023, Lovasz's team used compound fertilizers to significantly increase the yield and oil content of rapeseed, which can meet the increasing demand for biodiesel. In addition to planting methods, improving processing technology is also important. Some new technologies in recent years (such as "ultrasound-assisted transesterification" and "in situ transesterification") can make the production of biodiesel more efficient and more environmentally friendly (Almasi et al., 2019; Santaraite et al., 2020).

This study hopes to summarize several important factors that affect rapeseed oil production and find ways to optimize these factors to make the biodiesel production process more efficient and environmentally friendly. We

mainly studied several different agricultural practices (such as fertilization methods and variety selection) to observe their effects on rapeseed yield and oil content, and at the same time figure out the principles of emerging processing technologies to improve oil extraction and oil production efficiency. At the end of the study, we combined the environmental and economic effects of these methods to comprehensively evaluate the potential of these improvement methods. This study covers all aspects from field planting to factory processing, hoping to find a set of optimal solutions that can both increase yield and ensure quality, and enhance the sustainability of biodiesel production.

2 Genetic Improvements for Higher Oil Content

2.1 Advances in breeding techniques

In the past, people usually used some more traditional methods (such as hybridization and mutation breeding) to improve rapeseed. These methods have been used for many years, mainly to increase the oil content of rapeseed. Through breeding from generation to generation, researchers screened and retained good traits and cultivated many excellent improved varieties. There is a chemical mutagen called EMS. After treating rapeseed with EMS, new rapeseed varieties with high oleic acid content and low linolenic acid content can be obtained. At first, the agricultural performance of these varieties was not good. In order to improve the agricultural performance of this variety, scientists used "marker-assisted selection" technology to improve these varieties, which not only increased the oil yield of the new varieties, but also reduced the cost of planting (Spasibionek et al., 2020).

2.2 Identification of key yield-related genes

Recent studies have found that some key genes directly affect rapeseed oil content (SOC) and yield-related traits. For example, there is a gene called SFAR, which is related to the synthesis of fatty acids. The researchers used CRISPR-Cas9 technology to modify this gene, which increased the oil content without affecting seed germination and vitality (Karunarathna et al., 2020). Zhang et al. (2023) used the GWAS (genome-wide association analysis) method in their study and found a number of genes related to yield. These genes affect the number of siliques, the number of seeds in each silique, and the weight of seeds. They also combined transcriptome analysis to further find candidate genes such as RNA helicase and lipase, which also have a certain effect on yield. These findings provide very useful gene targets for subsequent variety improvement (Zhang et al., 2023).

2.3 Application of genomic selection and CRISPR-Cas9

The emergence of CRISPR-Cas9 technology has made the improvement of rapeseed much faster. It can modify certain genes very accurately, helping us to breed excellent varieties faster. In the study by Liu et al. (2022), researchers used this technology to modify the BnFAD2 gene, resulting in a significant increase in the oleic acid content in rapeseed. Zhang et al. (2019) knocked out multiple copies of the *BnLPAT2* and *BnLPAT5* gene families, which also resulted in higher oil production. This technology was also used to modify the EPSPS gene to breed rapeseed varieties that are resistant to herbicides (glyphosate). This shows that CRISPR can not only increase yield, but also improve quality (Wang et al., 2021). In polyploid crops such as *Brassica napus*, there are still some problems, such as the easy occurrence of non-target modifications (off-target effects) or multiple genes with duplicate functions. However, with the advancement of technology, these problems are gradually being solved, and the efficiency and scope of application are constantly improving (Figure 1) (Sandgrind, 2022; Tian et al., 2022; Ali and Zhang, 2023).

3 Agronomic Practices Enhancing Oil Yield

3.1 Soil and nutrient management

To increase the yield of rapeseed, soil and nutrient management are particularly important. Studies have found that adding biochar to the soil can bring many benefits. For example, it can increase the pH of the soil, increase the available phosphorus and organic carbon in the soil, and help the soil better retain water. These improvements can make rapeseed grow better and have higher yields. These effects will not last forever. Over time, the effect of biochar will weaken, so the soil needs to continue to be managed regularly (Jin et al., 2019). In addition to adding biochar, the rational application of fertilizers such as nitrogen, phosphorus, potassium, sulfur and boron can also

make rapeseed grow more vigorously. This not only allows the plant to accumulate more dry matter, but also increases the oil content of the seeds, and finally the total yield and profit will be higher (Tian et al., 2020). In acidic soils, if lime is added, as well as trace elements such as zinc, boron and molybdenum, it can also improve the pH and organic carbon content of the soil, while making the nutrients in the soil richer. These changes can improve soil quality and production capacity (Tanner et al., 2023).

Figure 1 The steps involved in CRISPR technology for seed oil improvement in *Brassica napus* (Adopted from Ali and Zhang, 2023)

3.2 Optimized planting densities and irrigation practices

In addition to soil management, planting density and irrigation methods also have a great impact on rapeseed yields. Field experiments have found that planting rapeseed more densely and applying fertilizer appropriately can make the plants grow denser, and the dry matter and oil content of the output are significantly increased (Tian et al., 2020). Some water-saving methods are also particularly effective in areas with water shortages or climate change. Spreading some straw in the field or using ridges to collect rainwater can improve water use efficiency and nutrient absorption capacity. Not only can it allow crops to absorb more water and nutrients, it can also reduce nutrient loss during the rainy season and keep the soil moist during the dry season. Doing so will ultimately increase the oil content in rapeseed (Feng et al., 2020).

3.3 Integrated pest and disease management

In order to maintain the high efficiency of oil production, the issue of pest and disease management cannot be ignored. Integrated pest and disease management (IPDM) is an effective method of pest and disease control. Zhang et al. (2020) found in their study that good weeding and drainage during rapeseed cultivation can significantly increase rapeseed yields. With other conditions unchanged, weeding alone can increase rapeseed yields by about 45.6%. Leaving rapeseed straw in the field after harvest can increase the organic matter, microbial count and enzyme activity in the soil, improve the health of the soil, and is also conducive to rapeseed growth. At the same time, it can also reduce the risk of heavy metal (especially cadmium) pollution. These management methods not only make crops grow better, but also make the entire planting environment safer and more suitable for rapeseed growth (Yang et al., 2020; Das et al., 2023).

4 Case Study: Implementing Precision Agriculture for Rapeseed Yield Optimization

4.1 Background and selection of study area

The study was conducted in northern Iran, a region with a favorable climate that is conducive to rapeseed cultivation. Both rain-fed and artificial irrigation methods have great potential here. We chose this region as a study site to see how different planting methods affect rapeseed yields. The diverse climate and rich soil types here provide a good environment for testing various agricultural technologies, especially those that increase oil production (Almasi et al., 2019).

4.2 Precision agriculture techniques applied

In order to increase rapeseed yield, we used many precision agriculture technologies. For example, we used "energy value analysis" to find out where energy is wasted and try to improve resource utilization efficiency. We also used support vector machines (SVM) and multi-objective genetic algorithms (MOGA) to predict and optimize the planting system. The boundary line method was also used in the study to estimate three yield indicators of rapeseed: one is the potential yield that can be achieved under ideal conditions (Yp), one is the actual level that can be achieved (Yatt), and the other is the current actual yield (Yact). In addition, we also tried to use different amounts of compound fertilizer to see if it had any effect on rapeseed and oil yield (Zhang et al., 2020; Esmaeilpour-Troujeni et al., 2021; Lovasz et al., 2023).

4.3 Measured improvements in oil yield and resource efficiency

After using these agricultural technologies, our yield and resource utilization have indeed improved a lot. For example, under the optimal planting conditions, we reduced the use of irrigation water, electricity and fungicides, but increased chemical fertilizers and organic fertilizers, resulting in a 24.55% increase in rapeseed yield. Under different conditions, rapeseed yields varied between 13.3 and 47.0 q/ha, and oil yields ranged from 629.8 to 2130.8 L/ha. Among them, the effect was most obvious when the amount of fertilizer was large, and the data was also statistically significant. These changes are also reflected in sustainability indicators. Under the best conditions, the comprehensive degree of perfection (CDP) reached 2.75 and the regeneration index (RI) also increased to 0.81 (Figure 2) (Zhang et al., 2019; Esmaeilpour-Troujeni et al., 2021; Lovasz et al., 2023).

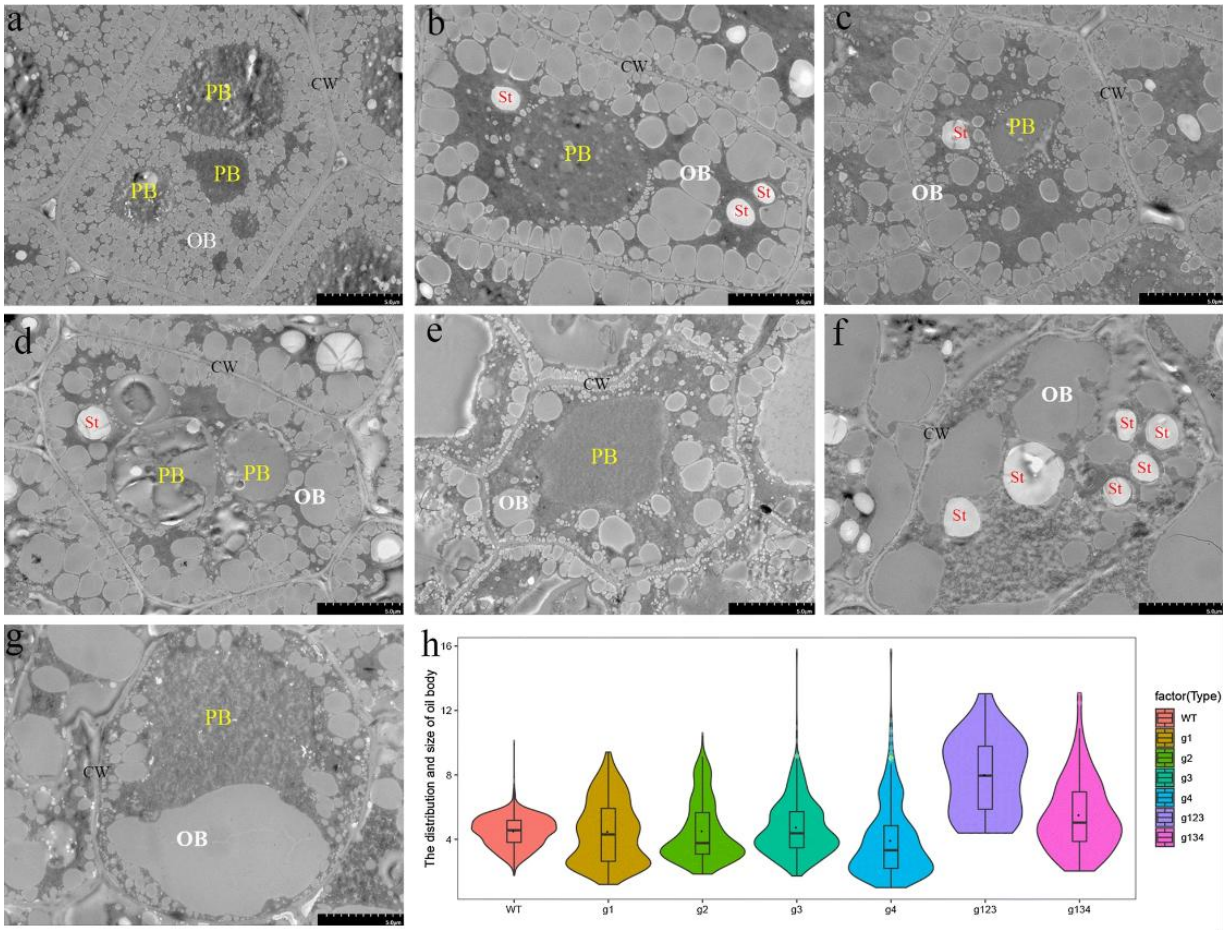

Figure 2 Ultrastructural study of Bnlpat2/5 knockout lines in mature cotyledons (Adopted from Zhang et al., 2019)

Image caption: a–g represent the mutant lines in WT, g1, g2, g3, g4, g123 and g134. OB indicates oil body, PB indicates protein body, St indicates starch, CW indicates well wall. h represents the distribution and the size of oil body size (Adopted from Zhang et al., 2019)

4.4 Economic and environmental impacts

Economic analysis shows that these advanced planting technologies not only increase yields, but also make rapeseed more cost-effective for biodiesel. In some places, such as the European Union, agricultural subsidy policies have also played a big role, encouraging farmers to adopt more environmentally friendly practices. In terms of the environment, studies have also seen obvious benefits. Pollution and greenhouse gas emissions are reduced. Biodiesel made from rapeseed oil has lower emissions than traditional diesel, and pollutants such as carbon monoxide (CO) and particulate matter are significantly lower. These results suggest that practices like conservation agriculture are not only good for the environment, but are also more economically stable and are an important means of achieving long-term sustainable agriculture (Saqib et al., 2012; Viccaro et al., 2019; Ganev et al., 2021).

5 Post-Harvest Processing for Maximum Oil Recovery

5.1 Advances in mechanical extraction

In recent years, mechanical extraction technology has made great progress in improving efficiency and environmental protection. Early mechanical extraction technology required several steps and was very energy-intensive. Now the new method has made the whole process simpler. The new technology can directly process the whole rapeseed into biodiesel without adding catalysts, and the whole process only requires one step (Tanner et al., 2023). The whole process reduces the use of water and solvents, which is more environmentally friendly. The new technology not only simplifies the extraction process, but also improves the yield and quality of the output oil, and has the hope of being put into large-scale production of biodiesel.

5.2 Role of solvent extraction and enzymatic processes

In order to extract as much oil as possible, solvent extraction and enzymatic processing play a key role. Especially when these two methods are combined, the effect is better and the oil yield can be significantly increased. There is a method of "in situ transesterification" that uses mineral diesel as an extraction solvent, which works very well (Santaraite et al., 2020; Sendžikienė et al., 2022). This method saves energy and money by eliminating the need to extract oil separately. Azócar et al. (2010) mixed used frying oil with rapeseed oil and used enzymes to react to increase the yield of fatty acid methyl esters (FAME). This shows that biodiesel can be made from cheap raw materials at low cost and high efficiency, which has great potential.

5.3 Quality control for biodiesel feedstock

Strict control of raw material quality is required to produce biodiesel that meets the standards. The physical and chemical properties of crude oil and processed biodiesel are usually tested to determine whether their quality meets the standards. Biodiesel produced from rapeseed oil generally meets the strict standards of Europe and the United States (Rashid and Anwar, 2008; Lovasz et al., 2023). Density, viscosity and sulfur content are key indicators for determining whether biodiesel can be used in engines. Optimizing reaction conditions and adjusting catalyst concentration and reaction temperature can also further improve oil quality and yield (Yuan et al., 2008; Saqib et al., 2012).

6 Sustainability Considerations in Rapeseed Oil Production

6.1 Environmental impacts of rapeseed cultivation

Although rapeseed has many advantages, it also has some disadvantages. Rapeseed cultivation may exacerbate global warming, acidification and eutrophication, mainly because fertilizers are used during the cultivation process, which will cause pollutants to be released from the soil. Different planting methods will change the carbon content in the soil, which will cause local climate change (Ganev et al., 2021). Pollutants emitted during rapeseed cultivation are one of the main sources of global and regional environmental problems. Although biodiesel made from rapeseed can reduce greenhouse gas emissions compared to traditional fuels (56% to 71% lower) (Herrmann et al., 2013), the pressure on the environment caused by the rapeseed cultivation process cannot be ignored, so we need to use more sophisticated planting methods to reduce the adverse impact on the environment.

6.2 Carbon footprint analysis of rapeseed-based biodiesel

Carbon footprint is an important reference for evaluating how environmentally friendly rapeseed biodiesel is. According to life cycle assessment (LCA), this biodiesel emits much less carbon during production and use than traditional fossil fuels. For a car that runs 1 000 kilometers, if it uses biodiesel, it will emit about 57 kilograms of carbon dioxide equivalent, while if it uses ordinary diesel, the emissions can reach 214 kilograms (Malça et al., 2014). In addition, replacing some traditional materials can also help. For example, using biofumigants instead of chemical ones can save 134 grams of carbon emissions per megajoule of biodiesel (Tanner et al., 2023).

6.3 Strategies for minimizing waste and enhancing circularity

To make the rapeseed oil production process more environmentally friendly, the key is to reduce waste and strengthen recycling. Byproducts of the production process can be used: the oil cake after oil extraction can be used to feed animals or used as a biofumigant, making the entire bioenergy chain more sustainable (Lovasz et al., 2023). Tanner et al. (2023) developed a new method in which they directly used whole rapeseed to produce biodiesel without using catalysts, too much water or solvents. This method is simpler and emits fewer pollutants. Another effective strategy is to use conservation agriculture to grow different crops in an area and reduce arable land (Yang et al., 2021) (Figure 3).

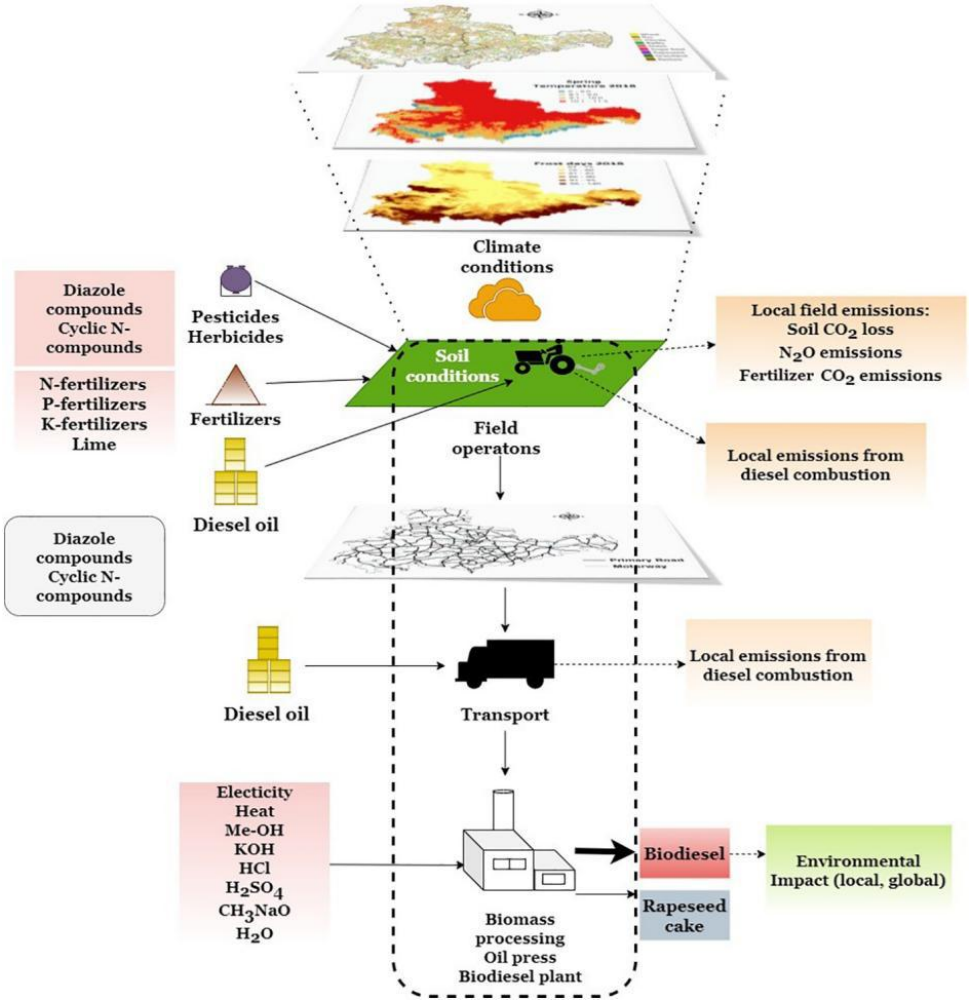

Figure 3 System boundary for the production of biodiesel from rapeseed (Adopted from Yang et al., 2021)

Image caption: The foreground is the region with agricultural crop cultivation. The geospatial maps of dominant crop distribution, regional climatic conditions and soil types are used to characterize the site-specific condition of rapeseed cultivation areas. The left side shows inputs for rapeseed cultivation, transportation to biodiesel plants and transesterification processing. The middle segment illustrates the major life cycle process of rapeseed-based biodiesel production, and the corresponding environmental impacts are shown on the right (Adopted from Yang et al., 2021)

7 Global Trends and Market Opportunities

7.1 Rapeseed oil production in key biodiesel markets

Rapeseed oil is one of the main raw materials for biodiesel, especially in Europe, where it is most widely used. In some places with suitable climates, such as Iran, the area of rapeseed cultivation has increased significantly. By improving planting and processing methods, local yields and efficiency have also increased (Almasi et al., 2019). In high-altitude areas such as the Qinghai Plateau in China, rapeseed yields are also relatively high due to the special climate and environment. Therefore, these areas have become one of the important production areas of rapeseed oil (Xiong et al., 2022). The energy efficiency of using rapeseed oil to make biodiesel varies greatly in different regions of Europe. Some places are highly efficient, while others have more serious energy waste. This shows that in some areas, better technology is needed to reduce losses and make this production method more feasible (Duren et al., 2019).

7.2 Policy incentives and challenges

The EU has introduced a number of policies to promote the use of clean energy. For example, they stipulate that by 2020, at least 10% of the energy used in the transportation industry must come from renewable energy (Herrmann et al., 2013). Such policies encourage sustainable agriculture and provide economic support for some small-scale biodiesel projects. Take Italy as an example. Conservation agriculture is promoted locally, which allows small farmers to participate in biofuel production while taking into account economic benefits and environmental protection (Viccaro et al., 2019). But this road is not without difficulties. Extreme weather such as drought will affect the yield and stability of rapeseed supply (Yang et al., 2021). Moreover, to start large-scale biodiesel production, it takes a lot of money and an efficient supply chain to cooperate. These have become important obstacles to the promotion of biodiesel (Viccaro et al., 2019).

7.3 Future prospects in sustainable energy

Rapeseed oil has a lot of room for development in the future biodiesel sector, and many current studies are focusing on optimizing processing and increasing crop yields. New technologies have emerged, including ultrasound-assisted methods and enzyme-catalyzed in situ transesterification, which can make the production process more efficient and less polluting (Almasi et al., 2019). Scientists use breeding methods to develop higher-yielding rapeseed varieties, and planting high-yield rapeseed varieties in special ecological environments can further increase yields (Abbadi and Leckband, 2011; Xiong et al., 2022). With strong policy support for renewable energy research and practice, rapeseed oil is expected to play an important role in the future energy transition.

8 Conclusion

There have been many studies that have yielded important findings and insights into achieving sustainable biodiesel production by increasing rapeseed oil yields. Experiments have shown that the use of compound fertilizers when growing rapeseed can significantly increase rapeseed and oil yields. To a certain extent, the more compound fertilizers are used, the higher the rapeseed oil yield, which is critical to increasing biodiesel yields. In terms of processing, researchers have optimized transesterification technology to achieve higher biodiesel yields and quality. Under appropriate optimal conditions, the base-catalyzed method can achieve a biodiesel yield of 95% to 96%; the ultrasound-assisted method can reach 87.175%. Another method, heterogeneous catalysis using sodium-modified fluoroapatite as a catalyst, can even achieve a biodiesel yield of 98%. These research results make rapeseed oil a promising biodiesel feedstock with high yield and good quality.

Looking forward, we believe that research on rapeseed can focus on optimizing fertilization programs. While working to increase rapeseed yields, it is also necessary to control the pressure on the environment caused by the rapeseed planting process. Excessive use of fertilizers can cause varying degrees of pollution to soil and water sources. Greener, more environmentally friendly and sustainable catalysts and reaction conditions can be studied to make the production process of biodiesel more efficient and environmentally friendly. We also need to understand clearly what positive and negative effects long-term use of biodiesel will have on engines, and

compare these effects with engines using traditional diesel. This information will be of great help in the future promotion of biodiesel. If renewable energy such as solar energy can be integrated into the biodiesel production process, it will further reduce costs and improve overall sustainability. It is also possible to consider using waste cooking oil or other non-edible oils as raw materials, which can not only reduce dependence on crops, but also promote the development of a circular economy. Rapeseed oil is an efficient and environmentally friendly biodiesel raw material and a viable alternative to fossil fuels. By improving planting and processing methods, it is expected to produce high-quality and high-standard biodiesel. At present, the demand for clean energy is increasing around the world. Biodiesel based on rapeseed can reduce carbon emissions and reduce dependence on non-renewable energy, which is a feasible way. Research in this field is still progressing. As long as we keep working hard, we can better tap the potential of rapeseed oil and realize a green energy future.

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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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