Engineering Perspectives in Filtration and Separation, Vol. 4, No. 3, September 2026
ISSN:3107-5290

Sustainable Conversion of Waste Cooking Oil into Biodiesel Through Agricultural Waste-Based Calcium Oxide Catalysis

Rustam Turakulov[1]*

[1]Professor, Department of Internal Medicine in Family Medicine, Tashkent State Medical University, Tashkent, Uzbekistan.*
E-mail: rustam.turakulov@tma.uz, Orcid: https://orcid.org/0000-0003-2204-2482

Abstract--- Increasing the demand for sustainable energy and the environmental challenges posed by the use of fossil fuel energy have promoted the generation of bio-fuels. Waste cooking oil (WCO) is a cheap source for the production of biodiesel; however, its efficiency in the biodiesel production process depends on the free fatty acid, moisture content and the reaction conditions. Traditional catalysts tend to incur relatively high costs for processing, chemical usage and recovery. It is, therefore, for this reason that this research focuses on optimizing biodiesel production from waste cooking oil by using CaO catalysts from agricultural wastes. What makes this research unique is the combination of valorisation of agricultural wastes and catalyst preparation to make a process that would economically and environmentally sustain biodiesel production. Agricultural and agro-industrial wastes rich in calcium are collected, cleaned, dried and thermally treated to prepare the CaO catalysts. Properties such as structure, composition, and morphology of the synthesized catalysts are characterized by techniques like X-ray diffraction, Fourier-transform infrared spectroscopy, and scanning electron microscopy. Used cooking oil will be filtered, dehydrated, and, if required, esterified using an acid before transesterification. Reaction parameters such as concentration of the catalysts, methanol-to-oil molar ratio, temperature, and reaction time are optimized using response surface methodology. Properties like yield of biodiesel, efficiency of conversion, reusability of catalyst, and selected properties of the fuel are investigated experimentally. It is anticipated that the planned research approach will show how waste-based CaO catalysts can contribute to efficient use of resources and minimize the dependence on chemical catalysts. The study offers a sustainable approach to convert wasted cooking oil and crop residues to renewable fuel.

Keyword--- Waste Cooking Oil, Biodiesel Production, Agricultural Waste, Calcium Oxide Catalyst, Heterogeneous Catalysis, Transesterification, Renewable Energy, Sustainable Fuel Development.

Received: 15 - 06 - 2026; Revised: 07 - 07 - 2026; Accepted: 17 - 08 - 2026; Published: 30 - 09 - 2026

I. Introduction

The consumption of fossil fuels in large quantities has created various issues, including pollution, emission of greenhouse gases, and problems related to the security of energy for the future. Biodiesel is one of the promising alternatives, as it is easily biodegradable and consists of low amounts of sulfur, along with being compatible with diesel engine technology. It can be made from vegetable oils, animal fats, and other waste lipid sources by chemical conversions. One of the most promising sources among these is waste cooking oil (WCO), which is relatively cheap and readily available while reducing the improper disposal of used cooking oil (Dong et al., 2025; Basumatary et al., 2018; Nasrollahzadeh et al., 2020).

Homogeneous alkaline catalysts like sodium hydroxide and potassium hydroxide are often used in the conventional process of biodiesel production. However, although these catalysts yield high conversion rates, they may form soap formation, cause separation problems, generate wastewater and require further purification processes. Heterogeneous CaO catalysts may provide an option since they are able not only to carry out the process of transesterification but also to make the separation of the products easier and possible to reuse the catalyst (Ghosh et al., 2024; Khan et al., 2020). Moreover, agricultural and agro-industrial wastes that contain calcium compounds can be used as a source for the production of CaO by controlled heating (Khan et al., 2021; Oloyede et al., 2023; Nath et al., 2023). This research will aim at producing biodiesel from waste cooking oil by using CaO catalysts made from calcium-containing agricultural wastes. It includes both waste recycling, catalyst synthesis and biodiesel production as a part of the sustainable processing system (Tsai & Tsai, 2024; Akream et al., 2024). The process of the catalyst synthesis will consist of cleaning, drying, calcination

and characterization to achieve the required catalytic activity. The innovation in this study comes from the combination of agricultural residue-derived CaO with optimization of reaction conditions through response surface methodology. Parameters like catalyst dosage, methanol to oil ratio, temperature of reaction, and time of reaction are taken into consideration to determine the optimal operating conditions. Yield of biodiesel, fuel properties, and recyclability of the catalysts are taken into account during performance evaluation. The objective of this study is to develop a viable method for conversion of waste materials into renewable energy.

Problem Statement

Waste cooking oil generation is becoming an increasing problem due to the risks associated with improper disposal which may lead to pollution of water resources and destruction of drainages, and increase in waste management problems. While WCO offers an affordable source of raw materials for biodiesel production, the high contents of free fatty acids and moisture in WCO can decrease the efficiency of conversion and increase unwanted soap formation. Also, the conventional heterogeneous catalysts bring about additional problems concerning separation of products, generation of wastewater and separation of the catalyst. Moreover, the disposal of calcium-rich agricultural and agro-industrial wastes is a potential area for development of sustainable catalytic materials. The existing methods of production need better combination of the preparation of the catalyst from waste materials, the pretreatment of the feedstock and the reaction. Thus, this work aims at the development of an efficient method for biodiesel production using CaO catalysts synthesized from the appropriate calcium-rich wastes.

Section Overview

The current manuscript describes an integrated study on biodiesel generation from waste cooking oil and calcium oxide catalysts prepared from agricultural residues. In the introduction, the background of the research is explained, including the motivation behind the study, environmental importance and issues encountered in the traditional production of biodiesel. The literature review section considers previous works done in the field with regards to converting waste oils, heterogeneous catalyst generation and optimization of the reactions. Research gaps are identified with regard to shortcomings of the present research. The methodology highlights the process of catalyst synthesis and the entire experiment.

II. Literature Review

Waste cooking oils have gained significant attention as another biodiesel source since they present an opportunity to decrease cost of biodiesel production while addressing the issue of environmental pollution from inappropriate waste oil disposal (Aderibigbe et al., 2023). The previous studies have looked at filtration, heating, dehydration and chemical pretreatment methods that enhance the quality of waste oil for subsequent transesterification process. Feedstock quality is still of importance since free fatty acid content may cause soap formation during alkali-catalyzed transesterification reaction. This means that acid esterification is a common approach if free fatty acids are present in high amount in the feedstock. Heterogeneous catalysts have been researched to address certain shortcomings related to homogenous catalysis. Calcium oxide appears to be especially promising due to its basic properties and availability. Catalytic activity is dependent on the method of preparation, surface characteristics, morphological features of the particles and impurities. Thermal treatment of waste materials with calcium content has been studied as the technology of production of catalytically active compounds. Agricultural and agro-industrial wastes, including eggshell waste, and other biological wastes with high content of calcium are potential sources of inexpensive CaO catalysts. But their chemical composition should be analyzed first. Transesterification is the key chemical reaction involved in the conversion of triglycerides in waste cooking oil into fatty acid methyl esters and glycerol. Methanol is usually chosen as the alcohol component due to availability and efficiency. Catalytic activity will depend on the concentration of the catalyst, alcohol-oil molar ratio, temperature, stirring intensity and reaction time. Lack of the catalyst will decrease conversion while its high concentration may cause problems with slurry separation.

Recently, there have been attempts in optimization methodologies that apply statistical experiment procedures such as response surface methodology to study interactions between reaction parameters and to find appropriate operating conditions. Catalyst characterization methods like X-ray diffraction, Fourier transform infrared spectroscopy, and scanning electron microscopy are equally crucial to learn about the structure and surface properties of materials. Quality of biodiesel can be assessed on the basis of its density, viscosity, acid value, flash point, and ester content. The ability of a catalyst to be reused is also another important issue in the economic sense (Etim & Bwapwa, 2025).

Research Gap

Even though there is literature concerning conversion of waste cooking oil and heterogeneous catalysts of calcium oxide, there are still research gaps that need addressing. Integration of the use of residues with high concentration of calcium and process optimization for biodiesel production needs further research. There are parameters such as the composition of residue, calcination temperature and the characteristics of the catalyst surface which affect the catalytic activity, but they do not get consideration together in many cases. Also, the interaction of catalyst loading, ratio of methanol to oil, reaction temperature and reaction time needs further evaluation. Issues concerning catalyst reuse and the quality of fuel produced are areas which may limit application in practice.

III. Methodology

The suggested methodology involves the use of an experimental method of producing biodiesel from waste cooking oil using calcium oxide catalyst prepared from agricultural residue. The experiment involves the following six steps: gathering of raw materials, pretreatment of the feedstock, preparation of the catalyst, characterization of the catalyst, transesterification and optimization of its performance.

Collection and Pretreatment of Raw Materials

Waste cooking oil is collected from restaurants, food processing units and domestic cooking processes. The collected waste cooking oil is subjected to filtration to eliminate any suspended food particles and then heating to remove any moisture present. The properties of the initial feedstock are measured to include free fatty acids, acid value and moisture content. In cases where the free fatty acid content is high, acid esterification is conducted before alkaline transesterification process. Agricultural residues rich in calcium such as discarded egg shells are collected separately. These residues are then washed, dried and crushed.

Preparation of Calcium Oxide Catalysts

The calcination of the prepared calcium-rich residues is done in a furnace in controlled manner to change the form of calcium carbonate to calcium oxide. The material calcined is cooled in moisture-free environment, ground and sieved to get homogenous catalyst powder.

The major conversion reaction taking place in equation (1):

$$CaCO_3 \xrightarrow{\Delta} CaO + CO_2 \quad (1)$$

The preparation temperature and time are chosen through experiments to obtain desired catalyst characteristics.

Catalyst Characterization

The characterization of the prepared catalyst is done by:

- XRD: For crystalline phases and formation of CaO.
- FTIR: For chemical bonding and functional groups.
- SEM: For surface morphology and particle structure.
- EDS: For elemental composition.

Biodiesel Production through Transesterification

The pre-treated waste cooking oil is heated to the desired temperature for reaction. The methanol and the prepared CaO catalyst are added based on the experimental conditions chosen. Stirring is done throughout the process to ensure better contact of the reactants and catalyst.

The transesterification reaction leads to conversion of triglycerides to fatty acid methyl esters (FAME) and glycerol in equation (2) and equation (3).

$$\text{Triglycerides} + 3CH_3OH \quad (2)$$

$$\xrightarrow{CaO} 3RCOOCH_3 + \text{Glycerol} \quad (3)$$

Once the reaction is complete, the mixture is left to separate. The glycerol-containing layer is separated from the biodiesel containing layer. The biodiesel is then washed, dried and purified before its quality analysis.

Process Optimization

Response Surface Methodology (RSM) is used to optimize the operating parameters:

1. Concentration of the catalyst.
2. Alcohol to oil mole ratio.
3. Reaction temperature.
4. Reaction time.

A proper experimental design, like Box-Behnken Design, is used to study the effect of the factors and their interactions. Biodiesel yield is taken as the main response variable.

The regression equation (4):

$$Y = \beta_0 + \sum_{i=1}^{4} \beta_i X_i + \sum_{i=1}^{4} \beta_{ii} X_i^2 + \sum_{i<j} \beta_{ij} X_i X_j \qquad (4)$$

Where:

- Y = Predicted biodiesel yield.
- X_i, X_j = Independent process variables.
- β_0 = Intercept.
- β_i = Linear coefficients.
- β_{ii} = Quadratic coefficients.
- β_{ij} = Interaction coefficients.

Performance Evaluation

The biodiesel yield is determined on the basis of yield, efficiency of conversion, density, viscosity, acid value, flash point, and ester content. Catalyst recycling and reusability test is carried out to study its operational stability.

The biodiesel yield is given in equation (5):

$$\text{Biodiesel Yield (\%)} = \frac{\text{Mass of purified biodiesel}}{\text{Mass of initial oil}} \times 100 \qquad (5)$$

Proposed Architecture

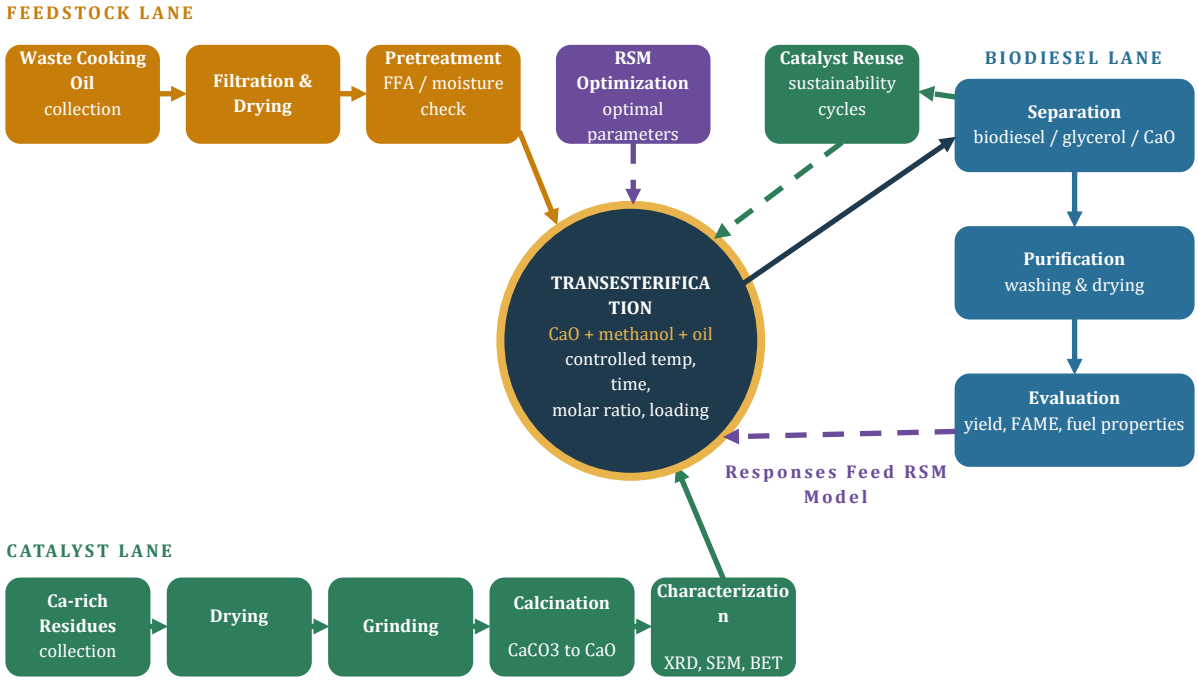


Figure 1: Proposed Experimental Architecture for Biodiesel Production Using Agricultural Residue-Derived CaO Catalysts

This proposed architecture provides a comprehensive experimental approach to produce biodiesel from waste cooking oil using agricultural residues-based CaO catalysts. The experiment starts with collection and

pretreatment of waste oil and residues containing calcium. Residues are dried, ground, and calcined to produce CaO catalysts and then characterized. The produced CaO catalyst is used in the transesterification reaction process. The biodiesel is then isolated and assessed. Response surface optimization determines appropriate operating conditions, whereas catalyst reusability experiments determine process sustainability.

The figure 1 shows the hub-and-lane experiment for biodiesel production. The pre-treated waste cooking oil and calcined agricultural residue CaO catalyst come together in the transesterification reaction. Biodiesel separation, purification, and testing are carried out. Response surface methodology helps to optimize the conditions based on the evaluation response, and catalyst recycling proves process sustainability.

Important Experimental Parameters

The parameters listed below have to be controlled systemically during experiments.

Table 1 shows the independent variables that have an effect on biodiesel production through the agricultural residue-derived CaO catalysts. The catalyst amount and the molar ratio of methanol and oil are directly related to the availability of catalytic sites and reactants; the temperature and reaction time affect conversion kinetics. The reusability of the catalyst gives additional information on the stability and cost-effectiveness of the synthesized catalyst.

Table 1: Major Experimental Parameters and Their Roles in Biodiesel Production

Parameter	Experimental significance	Evaluation approach
Catalyst loading	Influences catalytic activity and conversion	Different catalyst weight percentages
Methanol-to-oil ratio	Determines alcohol availability for transesterification	Different molar ratios
Reaction temperature	Influences reaction kinetics and mass transfer	Controlled heating
Reaction time	Determines the extent of triglyceride conversion	Different reaction durations
Catalyst reusability	Evaluates catalyst stability and economic feasibility	Repeated reaction cycles

IV. Technical Investigation of the Proposed System

Development and Characterization of Agricultural Residue-Derived Calcium Oxide Catalysts

Calcium oxide catalyst preparation using agriculture waste constitutes another significant part of the suggested biodiesel process. Sources of calcium carbonate for making the catalyst from biological waste material containing high levels of calcium, including eggshells which serve as food-processing waste, could be used. Thus, the use of the waste not only presents another possibility to produce the catalyst instead of purchased one but also allows solving the problem with food-processing waste disposal. First of all, the waste is washed in order to remove organic impurities. Then it is dried and ground into fine particles for further processing homogeneity. Next, calcination process is carried out to transform calcium carbonate into calcium oxide due to thermal decomposition. During calcination process, the control of temperature and time is very important since insufficient thermal processing leads to incomplete transformation and over-processing leads to sintering of particles and decreasing of the surface area. The obtained catalyst is ground and sieved in order to achieve uniform particle size. Moisture is not accumulated during storing since the calcium oxide could react with the atmosphere water and CO2.

X-ray diffraction is used to characterize the synthesized product to ascertain the existence of different crystalline phases as well as CaO. Fourier-transform infrared spectroscopy is used to determine the chemical bonding and functional groups on the surface of the catalyst. Scanning electron microscopy, on the other hand, is employed to assess the surface morphology of the particles. Energy-dispersive X-ray spectroscopy may also be used to characterize the elemental composition of the catalyst. This characterization determines whether the residue-based material has any favorable properties for transesterification. The catalysts are then tested through preliminary biodiesel production experiments. The catalyst activity is determined through biodiesel yields and performance of the conversion reaction. This study explores the relationship between processing of agricultural residues and biodiesel production through catalysts. In addition, reusability tests will also be conducted for deactivation of the catalysts.

Optimization of Transesterification and Biodiesel Production Performance

Optimization of the transesterification process is a critical aspect in order to achieve high conversion of biodiesel along with good efficiency in terms of resource usage. The waste cooking oil has the presence of triglycerides which will undergo reaction with methanol in the presence of a calcium oxide catalyst producing fatty acid methyl esters and glycerol. But the efficiency of the reaction is influenced by several operating factors

simultaneously. Hence, the proposed study uses the technique of Response Surface Methodology in order to analyze the factors such as the catalyst loading, the molar ratio of methanol to oil and the reaction temperature and time. The catalyst loading factor has an impact on the number of active sites present in the reaction mixture. Low amounts of catalyst may lead to incomplete triglyceride conversion while high loading may lead to increased mixture viscosity and side reactions.

Response surface method allows the creation of a statistical approach to finding the proper values of these variables. An analysis of variance is performed on experimental data that has been modeled by a quadratic equation to test for the significance of each variable and its interactions. The optimum is then validated using confirmation tests. The biodiesel obtained from the process is purified and analyzed based on some of the parameters related to fuel quality, such as density, viscosity, acid value and ester content. Tests can be done on the catalysts to determine the reusability of the catalysts.

Combining process optimization and biodiesel quality analysis helps create an efficient and economically viable process.

V. Graphical Evaluation

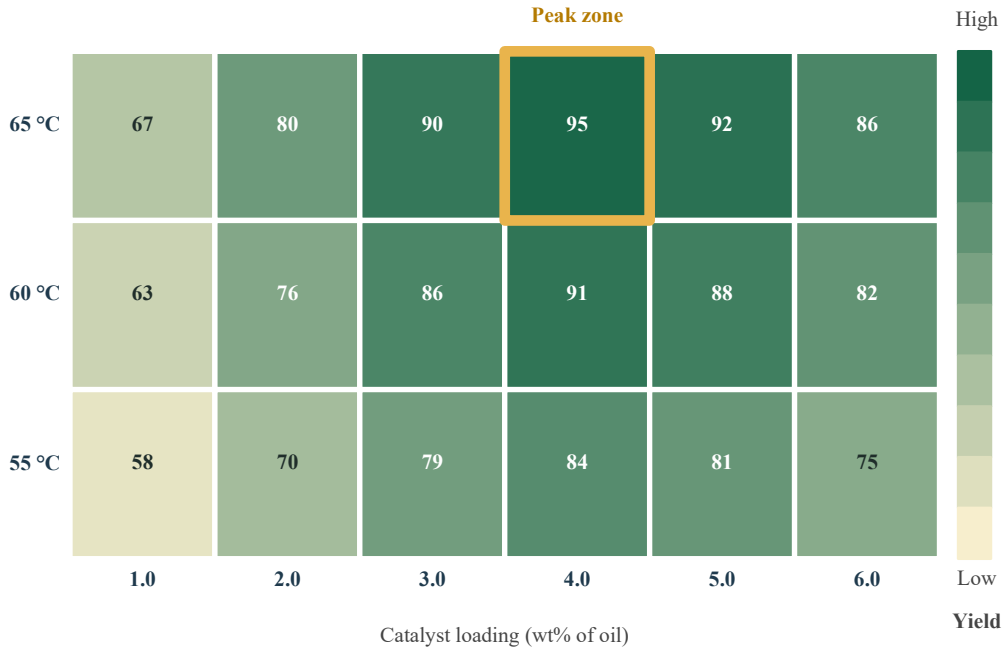


Figure 2: Illustrative Influence of Catalyst Loading on Biodiesel Yield at Different Reaction Temperatures

Figure 2 shows the multi-line graph shows how the amount of catalyst loading is related to biodiesel production at three different temperatures. From the graph, there is a gradual increase in the biodiesel production with an increase in the catalyst loading and after a certain level of loading, there is a fall in the biodiesel production. With respect to the reaction temperature, there is a relatively higher production at higher temperatures within the graph range. This graph is an example of why it is important to have a suitable catalyst loading and not to increase the amount of the catalyst.

VI. Discussion

The research involves the use of waste cooking oils in the preparation of calcium oxide catalysts using agricultural wastes rich in calcium. This technique provides an avenue for the assessment of the correlation between catalyst attributes and biodiesel production efficiency. Catalyst loading, methanol to oil ratio, reaction temperature, and reaction time are some of the factors that affect the transesterification process. The response surface methodology is useful in the identification of the correlations among these operational parameters and determination of the ideal reaction conditions. The graphical analysis proposed highlights the expected non-linear relationship between catalyst concentration and biodiesel yield although experimental confirmation is required. Catalyst characterization using XRD, FTIR, and SEM further yields other details about catalyst

structure and morphology. Repeated tests can also help in the detection of any catalyst deactivation or recovery challenges.

Challenges in the Proposed Research

Use of agricultural residue-based CaO catalysts for biodiesel production encounters various technical difficulties. The waste cooking oil has different compositions according to cooking practices, heat, and storage temperatures. High free fatty acid levels in waste oil lead to soap formation and separation difficulties of biodiesel. Differences in compositions of agricultural residues and calcination processes may have an effect on CaO and its catalytic performance. Moreover, CaO is susceptible to moisture and carbon dioxide in air, thus resulting in loss of its catalytically active surface characteristics. Limited compatibility between oil and methanol causes mass transfer difficulties. Catalyst deactivation can happen due to contamination, surface changes, and catalyst reusing. Energy requirements in drying, heating the feedstocks, and calcining the catalyst raise energy cost in biodiesel production process. In addition, it is important to purify the produced biodiesel from methanol, glycerol, catalyst particles, and unused oil.

Future Recommendations

Future studies can explore other economical sources of calcium-based agriculture and agro-industry residues for use as catalysts. Modification of the catalyst through metal supported CaO and composites can be used to enhance its catalytic efficiency, stability, and reusability. Optimization strategies like genetic algorithms and machine learning along with response surface methodology can be used in combination to develop the most effective reaction conditions. The development of a successful procedure for catalyst regeneration in order to regain its catalytic properties after repetitive production processes is needed. Moreover, future studies can conduct pilot plant experiments to determine the feasibility and scalability of the process. Life cycle assessment and techno-economic analyses can help to determine the costs of biodiesel production and other sustainability aspects. Finally, future research must focus on biodiesel stability during storage, resistance to oxidation, and engine performance in order to determine fuel reliability.

VII. Conclusion

This research focuses on establishing an effective and environmentally friendly biodiesel manufacturing process based on the use of waste cooking oils and calcium oxide catalysts prepared from agricultural wastes. This study takes into account the problems arising from the poor disposal of waste oils and low utilization of agriculture and agro-industry products with high amounts of calcium. What makes this research innovative is the combination of catalyst preparation from agricultural wastes, transformation of waste oils and the optimization of the reaction process. Waste cooking oils will be collected and pretreated, catalysts of calcium oxide will be prepared by calcination, the synthesis products will be characterized and transesterification will take place under varied conditions. Response surface methodology will be applied in order to evaluate the impact of catalyst amount, methanol to oil molar ratio, reaction temperature and time on biodiesel yield.

The anticipated outcome is the establishment of appropriate process conditions which could improve biodiesel production by employing agricultural waste as an alternative source for catalysts. Catalytic characterization is supposed to give information regarding the structure properties and how they affect catalytic properties. Moreover, the assessment of fuel quality will reveal whether the obtained biodiesel fulfills the fuel standards. The suggested optimization approach could help to increase process control and resource efficiency without the use of traditional catalysts. However, real improvements in the biodiesel production rate, costs and sustainability should be proven through experiments. Further study should be directed at regeneration of catalysts, alternative sources of residues, scale-up and life cycle assessment. Generally, the research provides a solid ground for the development of integration of agricultural waste utilization and biodiesel production via optimized heterogeneous catalytic process.

References

[1] Khan, H. M., Iqbal, T., Yasin, S., Ali, C. H., Abbas, M. M., Jamil, M. A., ... & Rahman, M. M. (2021). Application of agricultural waste as heterogeneous catalysts for biodiesel production. *Catalysts*, *11*(10), 1215. https://doi.org/10.3390/catal11101215

[2] Dong, Z., Dong, K., Li, H., Zhang, L., & Wang, Y. (2025). Progress and challenges in the process of using solid waste as a catalyst for biodiesel synthesis. *Molecules*, *30*(15), 3243. https://doi.org/10.3390/molecules30153243

[3] Etim, A. O., & Bwapwa, J. K. (2025). Optimization, economic assessment, and quality analyses of waste-based biodiesel fuel production: a case study of waste cooking oil and a seashell synthesized catalyst. *Energies*, *19*(1), 48. https://doi.org/10.3390/en19010048

[4] Ghosh, N., Patra, M., & Halder, G. (2024). Current advances and future outlook of heterogeneous catalytic transesterification towards biodiesel production from waste cooking oil. *Sustainable Energy & Fuels*, *8*(6), 1105-1152. https://doi.org/10.1039/d3se01564e

[5] Oloyede, C. T., Jekayinfa, S. O., Alade, A. O., Ogunkunle, O., Otung, N. A. U., & Laseinde, O. T. (2023). Exploration of agricultural residue ash as a solid green heterogeneous base catalyst for biodiesel production. *Engineering Reports*, *5*(1), e12585. https://doi.org/10.1002/eng2.12585

[6] Tsai, C. H., & Tsai, W. T. (2024). Sustainable processes reusing potassium-rich biomass ash as a green catalyst for biodiesel production: A mini-review. *Processes*, *12*(12), 2736. https://doi.org/10.3390/pr12122736

[7] Basumatary, S., Nath, B., & Kalita, P. (2018). Application of agro-waste derived materials as heterogeneous base catalysts for biodiesel synthesis. *Journal of Renewable and Sustainable Energy*, *10*(4). https://doi.org/10.1063/1.5043328

[8] Akream, N. S., Hamd, M. I., Gheni, S. A., Al-Sudani, F. T., Mohammed, A. E., Mohammed, H. R., ... & Tahah, A. K. (2024). High-yield activated carbon based ZnO-Ce bifunctional catalyst for production of biodiesel from waste cooking oil. *Energy Conversion and Management*, *321*, 119054. 10.1016/j.enconman.2024.119054

[9] Khan, H. M., Iqbal, T., Ali, C. H., Javaid, A., & Cheema, I. I. (2020). Sustainable biodiesel production from waste cooking oil utilizing waste ostrich (Struthio camelus) bones derived heterogeneous catalyst. *Fuel*, *277*, 118091. 10.1016/j.fuel.2020.118091

[10] Nath, B., Basumatary, B., Wary, N., Basumatary, U. R., Basumatary, J., Rokhum, S. L., ... & Basumatary, S. (2023). Agricultural waste-based heterogeneous catalyst for the production of biodiesel: a ranking study via the VIKOR method. *International Journal of Energy Research*, *2023*(1), 7208754. https://doi.org/10.1155/2023/7208754

[11] Aderibigbe, F. A., Saka, H. B., Mustapha, S. I., Amosa, M. K., Shiru, S., Tijani, I. A., ... & Bello, B. T. (2023). Waste cooking oil conversion to biodiesel using solid bifunctional catalysts. *ChemBioEng Reviews*, *10*(3), 293-310. https://doi.org/10.1002/cben.202200036

[12] Nasrollahzadeh, M., Soheili Bidgoli, N. S., Shafiei, N., Soleimani, F., Nezafat, Z., & Luque, R. (2020). Low-cost and sustainable (nano) catalysts derived from bone waste: catalytic applications and biofuels production. *Biofuels, Bioproducts and Biorefining*, *14*(6), 1197-1227. https://doi.org/10.1002/bbb.2138