

# Valorization of Low Quality Waste Cooking Oil (LQWCO) Via Catalytic Transesterification

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## ABSTRACT

The large volume of waste cooking oil (WCO) produced globally (~ 5.0 to 10.0 billion gallons/yr) and the associated market size of \$11.6 to \$12.8 billion USD inferred that the development of more valorization strategies is essential. One of the feasible upgrading options currently considered is the transesterification into biodiesel. However, developing catalyst that is resistant to FFAs and other impurities in the waste cooking oil (WCO) is still being investigated. We have herein demonstrated the successful development of a red mud (RM) material with good potential to catalyze very low quality waste cooking oil (LQWCO) upgrading. The LQWCO feed contains 37.50% of free fatty acids (FFAs) in addition to 4.5% of other impurities. Interestingly, for the transesterification reaction performed at 60°C using 0.3g of RM catalyst and 1:5 (oil: methanol) volume ratio for 1.0h, the RM catalyst produced 95.05% yield of biodiesel that was stable for five (5) repeated cycles of reaction. Additionally, the final biodiesel product contains negligible concentrations of FFAs, showing the ability of the RM material to catalyze combined in-situ esterification-transesterification process. The overall activity of this catalyst was much higher than that observed with each of the acid-modified charcoal systems (i.e. HSMC and HPMC). The RM catalyst was characterized to exhibit the oxides: Fe<sub>2</sub>O<sub>3</sub> (42.0%), Al<sub>2</sub>O<sub>3</sub> (22.5%), SiO<sub>2</sub> (15.5%), Na<sub>2</sub>O (12.0%) and CaO (8.0%). Thus, the overall activity could be associated to the synergic effects of the various active sites in these oxide systems. The RM catalyst has strong industrial potentials for upgrading of WCO of low quality.

**Keywords:** WCO; Low Quality; Red Mud; Transesterification; Potentials.

## 1.0 INTRODUCTION

The escalations in global energy demand across all regions due to economic advances and new energy policies inferred that the development of alternatives to compensate the widely utilized fossil fuels is necessary. Renewable and sustainable energy options are therefore being evaluated daily with the focus to ensure un-broken chain of energy production and utilization without any destruction to other sectors (i.e. including the environment) (Cui et al., 2026; Jafarli, 2026; Mwape et al., 2026). Among the renewable energy options under considerations, the biofuels are increasingly attracting attention globally. The common biofuels include biogas, bioethanol, biohydrocarbons (i.e. the gasoline, diesel, kerosene and jet fuel hydrocarbons derived from biomass conversion), biodiesel, etc. These biofuels are primarily derived from the upgrading of biomass via a number of processes that are thermochemical, physical, chemical and biological in nature (Ebadi et al., 2026; Galadima & Muraza, 2015; Idris et al., 2026; Talwar & Nanda, 2026; Zhang et al., 2026).

One of the biomass feedstock with potentials for energy applications is the waste cooking oil (i.e. WCO). Unlike the fresh vegetable oil or animal fat, the WCO is the product of several cycles of industrial or household

applications. Due to its poor quality that include large concentrations of free fatty acids (FFAs), water and residues, the WCO is primary considered as a waste product for disposals (Gul et al., 2025; Melikoglu, 2026). However, environmental pollution with associated contamination of water, agricultural land as well as the emission of harmful gases associated with the disposals necessitate the search for better handling options. Fortunately, the application of energy-based catalysis routes to valorize the WCO into fuel is increasingly being considered by industries and the researchers. The WCO can be transformed into fuel-range hydrocarbons like the gasoline and aviation fuels via hydrotreatment processes (i.e. hydrodeoxygenation and hydrodecarboxylation), biodiesel via combined esterification-transesterification or other biofuels through alternative thermochemical processes (Caporusso et al., 2025; Kanwar Gaur & Goyal, 2022; Rahman et al., 2025).

The conversion of the WCO into the biodiesel product is one these feasible valorization methods considered promising in the recent times. This can be achieved through the esterification-transesterification processes in a single-pot system. While the esterification converts the FFAs in the WCO, the transesterification process upgrades the mono-, di- and triglyceride esters in the

WCO into the biodiesel esters and glycerol. The transesterification process requires the application of suitable catalytic material and low molecular-weight alcohols like the methanol or ethanol and reaction temperatures commonly between 60 and 65°C (Dhore et al., 2026; Wen et al., 2026). Since the reaction is an equilibrium process requiring a mole ratio of 1:3 for oil to alcohol, the molar content of the alcohol is usually raised between 5:1 to 9:1 in order to favor forward reaction and ensure high yields of the biodiesel product.

Early industrial and laboratory-based transesterification reactions involved the utilization of homogeneous acid and/or base catalysts like H<sub>2</sub>SO<sub>4</sub>, HCl, NaO, KOH, etc. However, nonreusability and environmental disposal challenges have accounted for a shift to the heterogeneous catalyst systems. Among these latter materials, the oxides, zeolites, heteroplo acids and other modified materials have been substantially evaluated. However, problems of low yield due to slow reaction rates, catalyst leaching, poor-resistance to poisons in the vegetable oil feed like the FFAs and other challenges have triggered additional interest for the development of most promising eco-efficient catalyst systems (Galadima & Muraza, 2014; Wen et al., 2026). Therefore, taking this factor into serious cognizance, the current study targets the valorization of a low quality waste cooking oi (i.e. LQWCO) into biodiesel via the catalytic transesterification process. The roles of cheap catalysts such as red mud (RM) and various modified-charcoal systems (PC, HSMC and HPMC) as the catalytic candidates for the transesterification process were evaluated. The chemistry of the transesterification process had been substantially covered in some of our earlier publications (Galadima & Muraza, 2014, 2017, 2020).

## 2.0 EXPERIMENTAL

### 2.1 The Feedstock and Catalysts

The low quality waste cooking (LQWCO) and the charcoal precursor neem-tree used for this study were obtained from Kotorkoshi town of Bungudu Local Government in Zamfara State, Nigeria (Latitude: 12° 8' 26" to 12° 9' 21" N, Longitude: 6° 47' 11" to 6° 49' 19" E). On the other hand, the Red Mud (RM) was obtained from Makurdi in Benue State, Nigeria (7° 33' N to 7° 47' N and 8° 27' E to 8° 40' E). The LQWCO was subjected to physicochemical evaluations to establish its compositions using standard ASTM procedures for oil quality. The pure charcoal (PC) material was produced from the neem-tree precursor via local briquetting technique. It was modified with 1.0M each of H<sub>2</sub>SO<sub>4</sub> and H<sub>3</sub>PO<sub>4</sub> following 24h separate treatments and drying at room temperature for another 24h period. These modified

charcoal catalysts were later coded as HSMC and HPMC, respectively. The various catalysts were evaluated for their compositions and surface areas using, FT-IR, XRF and N<sub>2</sub>-adsorption studies with the aid of Fisher Scientific instruments.

**2.2 Transesterification Process:** The LQWCO was transesterified using as earlier procedure adopted by this group. Typically, an accurately weighed 0.3g of a catalyst was added to a glass reactor earlier charged with 20 cm<sup>3</sup> and 100 cm<sup>3</sup> of LQWCO and methanol, respectively. The resulted mixture was subjected to the reaction conditions of 400 rpm constant stirring, 60°C temperature and 1 h reaction time. The reaction products were gravity-separated with the aid of separation funnel. The quality of the biodiesel and other parameters were established in line with the standard procedures reported in ASTM-D6751.

## 3.0 RESULTS AND DISCUSSION

### 3.1 Characteristics of the LQWCO and the Catalysts:

Details on the various physicochemical properties of the LQWCO are presented in Table 1. The results showed that the composition of the triglyceride esters is only 35.0% with a total of 23.0% of mono- and diglyceride esters. It could also be observed that the FFAs have the highest composition. The compounds distribution for the LQWCO showed that the triglyceride esters have substantially underwent degradation and transformations into lower esters and FFAs during the Awara-frying process. Additionally, the content of other impurities such as water, debris and salts (i.e. 4.5%) revealed another possible challenge with the LQWCO due to associated chances of catalyst poisoning (Kim et al., 2026; Wen et al., 2026).

**Table 1. Physicochemical properties of the LQWCO.**

Parameter	Content (wt.%)
Triglyceride esters	35.0
Diglyceride esters	12.5
Monoglyceride esters	10.5
Free Fatty Acids	37.5
Other impurities (debris, salts, water)	4.5

Table 2 provides clear details about the compositions of each catalyst. The unmodified charcoal exhibits 100% of non-activated carbon without any expectation of catalytically active sites. Following modifications, the PC was activated with 10%-SO<sub>4</sub><sup>2-</sup> and 10%-PO<sub>4</sub><sup>3-</sup> to generate active acidic sites for the HSMC and HPMC catalysts, respectively. The RM catalyst contains mainly Fe<sub>2</sub>O<sub>3</sub> (42.0 wt.%) followed by Al<sub>2</sub>O<sub>3</sub> (22.5 wt.%) and SiO<sub>2</sub> (15.5 wt.%) with Na<sub>2</sub>O and CaO accounting for the balance compositions (i.e. 20.0 wt.%) consistently showing the material to be rich in basic sites. These type

of acidic and basic sites have been identified as good species for catalyzing acid-dependent reaction like the transesterification process (Banerjee & Chakraborty, 2009; Lam, Lee, & Mohamed, 2010; Sulaiman et al., 2025). According to the data presented in Table 3, the pore volume and associated BET surface area are catalyst-dependent. For the charcoal based catalysts, the introduction of acidic species generally reduced the surface area and the associated pore volume, the reduction being more pronounced for the HPMC catalyst modified with phosphoric acid. This factor could be due to the strong contraction effects of the phosphoric acid over the sulphuric acid. On the other hand, the RM catalyst exhibited the largest active BET surface area of 205 m<sup>2</sup>/g, which could be due to its unique chemical compositions and the synergic effects of the various metal-oxides.

**Table 2. Compositions of the various catalysts used for the transesterification process.**

Catalyst	Abbreviation	Composition (wt.%)
Red Mud	RM	Fe <sub>2</sub> O <sub>3</sub> (42.0%), Al <sub>2</sub> O <sub>3</sub> (22.5%), SiO <sub>2</sub> (15.5%), Na <sub>2</sub> O (12.0%) and CaO (8.0%)
Pure Charcoal	PC	100% Carbon
H <sub>2</sub> SO <sub>4</sub> -modified Charcoal	HSMC	10%-SO <sub>4</sub> <sup>2-</sup> , 90% Carbon
H <sub>3</sub> PO <sub>4</sub> -modified Charcoal	HPMC	10%-PO <sub>4</sub> <sup>3-</sup> , 90% Carbon

**Table 3. Physicochemical properties of the various catalysts from N<sub>2</sub> adsorption studies.**

Catalyst	Pore Volume (cm <sup>3</sup> /g)	Active BET Surface Area (m <sup>2</sup> /g)
RM	0.050	205
PC	0.075	150
HSMC	0.065	145
HPMC	0.060	143

**3.2 Transesterification Potentials:** The activity of each catalyst in the valorization of the LQWCO is depicted in Table 4. According to these results, the PC catalyst was the least active due to the absence of catalytic active sites to derive the process. This material produced only 30.25% yield of biodiesel. This low activity could not only be limited to lack of active sites, but also associated with poor resistance to attack by FFAs and other impurities in the LQWCO feedstock. Generally, for the other catalysts, the activity followed the trend HPMC < HSMC < RM, revealing the red mud (i.e. RM) as the most active catalytic material during the reaction due to its chemical compositions.

**Table 4. Yields of biodiesel for each catalyst. Reactions performed under the conditions 65°C, 6/1 (methanol/oil), 0.1g catalyst and 60 min.**

Catalyst	Biodiesel Yield (%)
RM	95.05
PC	30.25
HSMC	65.45
HPMC	63.35

The stability and resistance of any catalyst to FFAs and other impurities in any oil feedstock are very important in predicting its overall performance (Phan & Phan, 2008; Sudiyanto, 2026). Figure 1 provides the wt.% of recovered catalysts after five (5) application cycles in each case. It could be observed that the most active RM material exhibited the best stability properties. More than 99.5% of this catalyst was recovered from the products after the transesterification process. This promising factor revealed an excellent resistance of the RM catalyst to deactivation of leaching. For the charcoal-based catalysts, the trend of catalyst stability followed the order HPMC < HSMC < PC, indicating that the unmodified charcoal was fundamentally more stable among the three (3) catalysts. This factor could be due to the absence of susceptible active sites with the PC material. These results also displayed consistent agreement with the content of FFAs found in the final biodiesel product as illustrated in Figure 2. The largest content of FFAs (nearly 35%) found with the PC catalyst indicated poor transformation of these species into biodiesel via in-situ esterification over the PC system (Galadima & Muraza, 2014; Sudiyanto, 2026). Additionally, this factor is consistent with the absence of active sites with this specific material. Generally, the biodiesel produced with the RM catalyst had the lowest (i.e. < 0.5%) of the FFAs. This could be due to associated resistance of the FFAs poisons and the susceptibility of this catalyst to transform the FFAs into biodiesel esters via in-situ esterification. Generally, the results indicated the RM catalyst-derived biodiesel to be of high quality in line with the ASTM requirements.

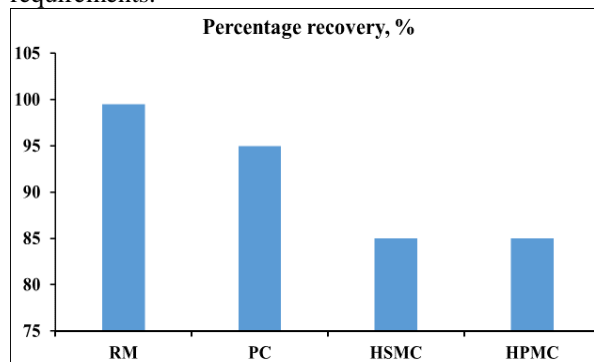


Figure 1. Recovered catalyst content after the reaction.

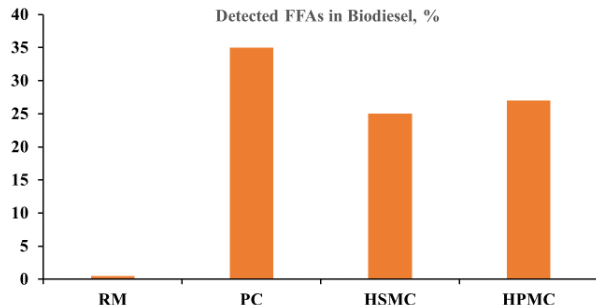


Figure 2. Percentage amount of unreacted free fatty acids (FFAs) found in the biodiesel product.

#### 4.0 CONCLUSION

Transesterification of oils with high content of FFAs and other impurities is seriously challenging due to active sites poisoning and consequent catalyst deactivation over time. In this study, we examined the role of four (4) different catalysts (i.e. PC, HSMC, HPMC and RM) in the valorization of a low quality waste cooking oil containing more than 40% of FFAs and other impurities. The overall catalytic activity obeys the trend RM > HSMC > HPMC > PC. The highest yield of 95.05% of biodiesel, ~100% recovery of catalysts after five (5) cycles of applications and the negligible content of post-transesterification FTAs in the product revealed superior and uncommon activity-stability properties with the RM catalysts than the other catalyst systems. Consequently, the RM catalyst has good industrial prospects for the upgrading of LQWCO from household or industrial applications.

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#### REFERENCES

Banerjee, A., & Chakraborty, R. (2009). Parametric sensitivity in transesterification of waste cooking oil for biodiesel production—A review. *Resources, Conservation and Recycling*, 53(9), 490-497. doi:<https://doi.org/10.1016/j.resconrec.2009.04.003>

Caporusso, A., Radice, M., Biundo, A., Gorgoglione, R., Agrimi, G., & Pisano, I. (2025). Waste cooking oils as a sustainable feedstock for bio-based application: A systematic review. *Journal of Biotechnology*, 400, 48-65. doi:<https://doi.org/10.1016/j.jbiotec.2025.02.003>

Cui, H., Lv, X., Wang, G., Liang, D., Wang, X., Li, M., & Lv, X. (2026). Coupling optimization strategies for

renewable energy and hydrogen production systems: A review based on the VSEL framework. *Applied Energy*, 420, 128209. doi:<https://doi.org/10.1016/j.apenergy.2026.128209>

Dhore, A. R., Rajak, A. K., Mishra, P., Yadav, M., Prus, P., Srivastava, V., . . . Sarangi, P. K. (2026). Sustainable biodiesel production from non-edible feed stocks: A review on enzymatic transesterification. *Molecular Catalysis*, 598, 116004. doi:<https://doi.org/10.1016/j.mcat.2026.116004>

Ebadi, S., Lee, J., Nam, H., Jung, S., Seo, M. W., Lee, D., & Park, Y.-K. (2026). Critical review on the production of quality-enhanced bio-oil from co-pyrolysis of lignocellulosic biomass and common plastics waste. *Industrial Crops and Products*, 249, 123655. doi:<https://doi.org/10.1016/j.indcrop.2026.123655>

Galadima, A., & Muraza, O. (2014). Biodiesel production from algae by using heterogeneous catalysts: A critical review. *Energy*, 78, 72-83. doi:<https://doi.org/10.1016/j.energy.2014.06.018>

Galadima, A., & Muraza, O. (2015). Catalytic upgrading of vegetable oils into jet fuels range hydrocarbons using heterogeneous catalysts: A review. *Journal of Industrial and Engineering Chemistry*, 29, 12-23. doi:<https://doi.org/10.1016/j.jiec.2015.03.030>

Galadima, A., & Muraza, O. (2017). Sustainable Production of Glycerol Carbonate from By-product in Biodiesel Plant. *Waste and Biomass Valorization*, 8(1), 141-152. doi:10.1007/s12649-016-9560-y

Galadima, A., & Muraza, O. (2020). Waste materials for production of biodiesel catalysts: Technological status and prospects. *Journal of Cleaner Production*, 263, 121358. doi:<https://doi.org/10.1016/j.jclepro.2020.121358>

Gul, W. A., Mohd Hasan, M. R., Jameel, M., Kamal, K., Mohd Ghazali, M. F. H., Zakaria, Z., & Yang, X. (2025). Waste cooking oil potential as a green rejuvenator to restore the aged binder properties in reclaimed asphalt pavement: A state-of-the-art review. *Journal of Traffic and Transportation Engineering (English Edition)*, 12(5), 1125-1149. doi:<https://doi.org/10.1016/j.jtte.2025.03.002>

Idris, R., Chong, W. W. F., Ng, J.-H., Mahari, W. A. W., Lam, S. S., Mong, G. R., . . . Nyakuma, B. B. (2026). A review on non-catalytic and catalytic co-pyrolysis of waste tire and biomass for upgrading pyrolysis oil. *Renewable and Sustainable Energy Reviews*, 239, 117117. doi:<https://doi.org/10.1016/j.rser.2026.117117>

Jafarli, O. (2026). Assessment of renewable energy potential for heating applications in Azerbaijan: A review and regional perspective. *Energy Conversion*

- and Management: X, 30, 101908.  
doi:<https://doi.org/10.1016/j.ecmx.2026.101908>
- Kanwar Gaur, R., & Goyal, R. (2022). A review: Effect on performance and emission characteristics of waste cooking oil Biodiesel- diesel blends on IC engine. *Materials Today: Proceedings*, 63, 643-646. doi:<https://doi.org/10.1016/j.matpr.2022.04.447>
- Kim, M., Lee, S., Lee, T., Lee, C.-G., Lee, J., & Kwon, E. E. (2026). Biodiesel production through thermally induced transesterification from waste cooking oil using calcium phosphate catalyst. *Fuel*, 415, 138491. doi:<https://doi.org/10.1016/j.fuel.2026.138491>
- Lam, M. K., Lee, K. T., & Mohamed, A. R. (2010). Homogeneous, heterogeneous and enzymatic catalysis for transesterification of high free fatty acid oil (waste cooking oil) to biodiesel: A review. *Biotechnology Advances*, 28(4), 500-518. doi:<https://doi.org/10.1016/j.biotechadv.2010.03.002>
- Melikoglu, M. (2026). Sustainable transformation of waste cooking oil: A global review of valorization pathways and future directions. *Next Materials*, 11, 101730. doi:<https://doi.org/10.1016/j.nxmte.2026.101730>
- Mwape, M. C., Kimutai, S. K., Nzila, C., Bett, R. K., Washika, T., Deng, M., . . . Hensel, O. (2026). The Renewable energy-Food processing-Sustainability Nexus: A PRISMA review of innovations, sustainability metrics and indicators. *Renewable and Sustainable Energy Reviews*, 237, 117005. doi:<https://doi.org/10.1016/j.rser.2026.117005>
- Phan, A. N., & Phan, T. M. (2008). Biodiesel production from waste cooking oils. *Fuel*, 87(17), 3490-3496. doi:<https://doi.org/10.1016/j.fuel.2008.07.008>
- Rahman, A., Oktaufik, M. A. M., Sasongko, T. W., Guntoro, I., Soedjati, D., Abbas, N., . . . Sasongko, N. A. (2025). Current scenario and potential of waste cooking oil as a feedstock for biodiesel production in Indonesia: Life cycle sustainability assessment (LCSA) review. *Case Studies in Chemical and Environmental Engineering*, 11, 101067. doi:<https://doi.org/10.1016/j.cscee.2024.101067>
- Sudiyanto, G. Z. (2026). Study on the potential of used cooking oil and microalgae as biodiesel feedstocks in Indonesia. *Respobio Journal*, 2(1), 37-48.
- Sulaiman, N. F., Gunasekaran, S. S., Mohd Nashruddin, S. N. A., Mohd Nashruddin, S. N. A., Sofiah, A. G. N., Abd Mubin, M. H., & Lee, S. L. (2025). Advancements in transesterification of waste cooking oil to biodiesel using rare earth metal oxide catalysts: A bibliometric analysis and future prospects. *Fuel*, 394, 135158. doi:<https://doi.org/10.1016/j.fuel.2025.135158>
- Talwar, P., & Nanda, S. (2026). Catalytic co-pyrolysis of lignocellulosic biomass and plastic waste for biofuel production: a review. *Biomass Futures*, 2, 100046. doi:<https://doi.org/10.1016/j.bmf.2026.100046>
- Wen, Y., Wang, Z., Li, J., Xue, C., Wang, H., Li, X., . . . Song, W. (2026). Current advances in heterogeneous catalysts based on hypercrosslinked polymers for transesterification in biodiesel production: A comprehensive review. *Chinese Chemical Letters*, 37(5), 111960. doi:<https://doi.org/10.1016/j.ccelet.2025.111960>
- Zhang, L., Zhang, Z., Dong, X., Wang, H., Fan, Q., Chen, H., & Ji, Y. (2026). Unlocking the synergistic pathways: A mini review on co-conversion of petroleum coke and lignocellulosic biomass. *Journal of Analytical and Applied Pyrolysis*, 197, 107835. doi:<https://doi.org/10.1016/j.jaap.2026.107835>