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PRODUCTION AND CHARACTERIZATION OF BIODIESEL FROM VARIABLE WASTE COOKING OIL FEEDSTOCKS VIA BASE-CATALYZED TRANSESTERIFICATION AND COMPARATIVE EVALUATION WITH DIESEL.

***Suriya K P, Prasath S, Raksha A V R**

Department of Chemical engineering, CIT Sandwich Polytechnic College, Coimbatore.

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***Corresponding Author: Suriya K P**

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ABSTRACT

The growing dependence on fossil fuels and the environmental burden caused by improper disposal of used cooking oil have intensified interest in renewable, waste-derived biofuels. In this study, biodiesel was produced from waste cooking oil (WCO) through a base-catalyzed transesterification process using potassium hydroxide as the catalyst and methanol as the alcohol reagent. The oils were collected from multiple local sources to represent practical variations in quality and free fatty acid content, then filtered and preheated to remove impurities and moisture prior to reaction. The process was carried out under optimized temperature, reaction time, and molar ratio conditions to achieve complete conversion. After separation, washing, and drying, a clear biodiesel phase was obtained that met the essential fuel performance and safety requirements for diesel engine operation. The produced biodiesel exhibited improved ignition quality, higher flash point, and comparable flow and combustion behavior when compared with conventional diesel fuel. The results confirm that even variable-quality WCO can be effectively converted into high-grade biodiesel using a simple, low-cost base-catalyzed method. This work highlights the potential of waste cooking oil as a sustainable feedstock for decentralized biodiesel production and demonstrates a practical pathway to reduce environmental pollution while contributing to renewable energy generation.

KEYWORDS: Waste cooking oil; Biodiesel; Base-catalyzed transesterification; Potassium hydroxide; Renewable fuel; Sustainable energy; Waste valorization.

1. INTRODUCTION

The rapid depletion of petroleum reserves and the tightening of global emission regulations have intensified the search for renewable fuels that can be produced locally and integrated into existing diesel infrastructure. Among several bio-based alternatives, biodiesel—a mixture of fatty acid methyl esters (FAMEs)—has gained particular attention due to its biodegradability, low sulfur content, and compatibility with compression-ignition engines [1–3]. However, large-scale production of biodiesel from edible vegetable oils has raised serious concerns regarding food security and land competition, redirecting research focus toward non-edible and waste-derived feedstocks [4–6].

Waste cooking oil (WCO) has emerged as one of the most promising of these feedstocks. It is inexpensive, abundant in urban areas, and represents a problematic waste stream that otherwise contributes to sewage blockage and environmental pollution [7]. Converting WCO into biodiesel not only supplies renewable energy but also mitigates solid and liquid waste disposal issues [8]. Despite these advantages, commercial exploitation remains limited by inconsistencies in the quality of collected WCO—including variations in free fatty acid (FFA) content, water, and degradation products resulting from repeated frying cycles [5, 9]. Such variability strongly affects transesterification efficiency, catalyst performance, and final fuel properties, yet many studies have relied on a single, idealized WCO sample, overlooking this fundamental challenge [10–12].

Earlier investigations have successfully demonstrated that base-catalyzed transesterification using NaOH or KOH is an efficient and economically viable method for low-FFA oils [2, 11]. Nevertheless, few systematic studies have explored how different grades or sources of WCO influence reaction behavior and biodiesel characteristics when using a simple alkali-based route. Similarly, although numerous reviews discuss heterogeneous or enzymatic catalysts [9, 13], data correlating feedstock variability with key fuel properties—such as viscosity, density, and calorific value—remain fragmented and inconsistent [6, 14]. This knowledge gap hinders the formulation of standardized protocols for small-scale biodiesel producers and complicates quality control during decentralized manufacturing.

In view of these limitations, the present study aims to produce and characterize biodiesel from variable WCO feedstocks collected from local sources using a base-catalyzed (KOH) transesterification process. The work further includes a comparative evaluation of the resulting fuel properties with conventional diesel, focusing on critical performance parameters such as viscosity, density, and flash point. By emphasizing real-world feedstock variability and measurable fuel characteristics rather than optimized laboratory conditions, this research seeks to bridge the gap between experimental feasibility and practical application, offering an accessible framework for sustainable waste-to-fuel conversion.

2. Literature Review

The conversion of triglyceride-based oils into fatty acid methyl esters (FAMEs) has been extensively examined since the early 1990s, yet the focus has gradually shifted from edible to waste-derived feedstocks due to cost and sustainability constraints [1, 4]. Among waste options, waste cooking oil (WCO) is particularly attractive because it can lower biodiesel production costs by up to 70 % compared with virgin oils [5]. Nevertheless, the chemical instability of WCO—caused by thermal degradation, oxidation, and polymerization during repeated frying—creates considerable variability in free fatty acid (FFA) levels, water content, and viscosity [6]. These variations complicate the transesterification reaction and are often ignored in laboratory-scale reports.

2.1 Feedstock quality and pretreatment requirements

Numerous researchers have emphasized that high FFA (> 2 %) or water content promotes saponification, leading to emulsion formation and yield loss when base catalysts are used [2, 7]. To address this, acid esterification pretreatment with sulfuric acid or p-toluenesulfonic acid has been employed to reduce FFA before the alkaline step [8]. Others have explored enzymatic or heterogeneous acid catalysts as single-step alternatives, but these typically require longer reaction times or higher costs [9, 10]. Despite wide documentation of these methods, most experiments rely on single, clean batches of WCO; comprehensive assessments across multiple, variable feedstocks remain scarce [5, 11].

2.2 Catalyst systems and reaction optimization

Homogeneous base catalysts such as NaOH and KOH continue to dominate because they offer high reaction rates under mild conditions (55–60 °C) and simple process control [2, 11]. Studies comparing NaOH and KOH suggest that potassium hydroxide provides easier phase separation and fewer soap residues due to higher solubility in methanol [12]. Researchers have optimized parameters such as methanol-to-oil molar ratio (6–9 : 1), catalyst loading (0.5–1.5 wt %), and reaction time (60–90 min) to achieve yields above 95 % for refined oils [3, 13]. However, performance often declines sharply when applied to degraded or mixed WCO sources [5].

To improve tolerance toward impurities, attention has turned to heterogeneous catalysts, including calcium oxide (CaO), magnesium oxide, and biomass-derived ashes [9, 15]. These solids simplify product separation and enable catalyst reuse, though their activity decreases after repeated cycles due to leaching and surface poisoning [10]. Advanced methods such as ultrasonic, microwave, and hydrodynamic cavitation-assisted transesterification have been explored to intensify reaction rates and reduce methanol usage [3, 4]. While promising, these techniques still depend on well-controlled feedstock conditions that may not represent real-world waste oil streams.

2.3 Fuel property evaluation and comparison with diesel

Property characterization remains essential to verify compliance with ASTM D6751 or EN 14214 specifications. Reported densities for WCO biodiesel typically range from 837 to 888 kg m^{-3}, while kinematic viscosities lie between 4.5 and 5.5 mm^2 s^{-1} at 40 °C, slightly above conventional diesel but within acceptable limits [6, 13]. The flash point of WCO biodiesel (160–180 °C) is substantially higher than that of diesel (~70 °C), improving safety in handling [14]. The calorific value averages around 39–41 MJ kg^{-1}, roughly 10 % lower than diesel [6]. Despite minor deviations, engine trials confirm that blends up to 20 % biodiesel (B20) maintain comparable power output and reduced smoke emissions [13]. Yet, literature shows inconsistent correlations between WCO feedstock properties (e.g., FFA, water, color) and resulting fuel parameters, partly because many studies omit detailed feedstock analysis or use lab-refined oil for simplicity [5, 10]. Consequently, reproducibility and predictive modeling of biodiesel quality remain unresolved.

2.4 Identified research gap

The reviewed literature clearly indicates substantial progress in catalyst development and reaction optimization but exposes a persistent disconnect between laboratory conditions and practical feedstock variability. Few investigations systematically compare biodiesel produced from multiple real WCO sources under identical base-catalyzed conditions to quantify how feedstock quality impacts yield and final fuel characteristics. Without such data, small-scale producers lack reliable guidance on process adjustments for different oil qualities.

Therefore, the present study addresses this gap by evaluating base-catalyzed transesterification of variable WCO feedstocks using KOH as the catalyst and examining the resulting biodiesel properties in direct comparison with commercial diesel. This approach combines experimental simplicity with real-world relevance, aiming to develop a practical framework for decentralized biodiesel production from heterogeneous waste resources.

3. Materials and Methods

3.1. Materials

The main raw material used in this study was waste cooking oil (WCO) collected from different local restaurants to represent realistic variability in feedstock quality. Each batch of WCO was filtered through a fine mesh to remove food particles and then heated to 110 °C for 15 minutes to evaporate moisture before use.

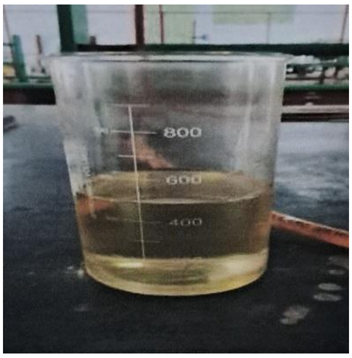


Fig. 1: Collected waste cooking oil samples

3.2. Pretreatment of Waste Cooking Oil

Fig. 2: Heating and conditioning of waste cooking oil prior to reaction.

Since WCO typically contains degraded compounds and varying levels of free fatty acids (FFA), the oil was visually inspected and subjected to heating and filtration pretreatment. The preheating at 110 °C also improved fluidity and removed trapped air and volatile contaminants. Samples were allowed to cool to approximately 50 °C before being used in the transesterification reaction.

3.3. Catalyst and Alcohol Preparation

The KOH–methanol catalyst solution was prepared by dissolving 1 wt % of KOH (based on oil mass) in methanol. The mixture was stirred magnetically until a clear solution was obtained, forming potassium methoxide—the active catalytic species responsible for initiating transesterification. To prevent moisture uptake, the solution was prepared freshly before each reaction and used immediately.

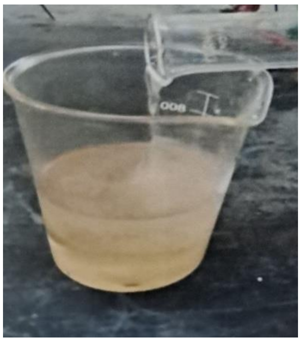


Fig. 3: Preparation of KOH–methanol catalyst solution.

3.4. Base-Catalyzed Transesterification

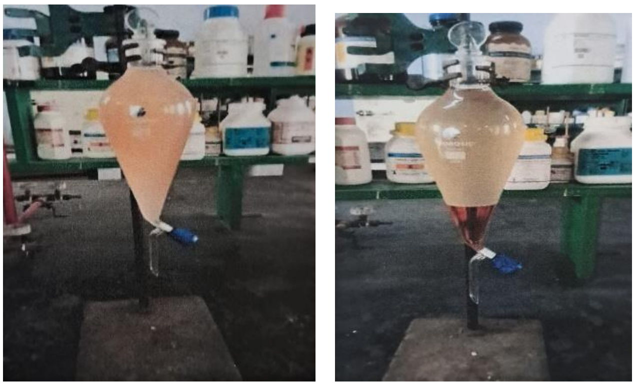
The transesterification reaction was performed in a 500 mL three-necked round-bottom flask equipped with a reflux condenser, thermometer, and mechanical stirrer. For each batch, 100 mL of pretreated WCO was reacted with methanol at a 6:1 molar ratio and 1 wt % KOH catalyst loading. The mixture was maintained at 55–60 °C for 60 minutes under continuous stirring at approximately 600 rpm. After reaction completion, the mixture was transferred to a separatory funnel and allowed to settle undisturbed for 12 hours to achieve clear phase separation.

Fig. 4: Transesterification setup.

3.5. Separation, Washing, and Drying

Following the settling period, two layers were distinctly observed:

- The upper layer (lighter phase) consisting of crude biodiesel, and
- The lower layer (heavier phase) consisting of glycerol, unreacted methanol, and catalyst residues.



(i) *(ii)*

Fig. 5: Settling of biodiesel and glycerol layers (i) before reaction (ii) after reaction.

4. RESULTS and DISCUSSION

4.1. Overview of Key Fuel Properties

The produced biodiesel samples from variable waste cooking oil (WCO) feedstocks were evaluated for essential physicochemical properties in accordance with ASTM D6751 and EN 14214 standards. These parameters determine the suitability of biodiesel as an alternative to conventional diesel fuel and influence engine performance, combustion efficiency, and emission behavior.

The key fuel properties analyzed include density, kinematic viscosity, flash point, acid value, cetane number, calorific value, and pour point. Comparative values of WCO biodiesel and commercial diesel are summarized in Table 4.1.

Table-4.1 Comparative values of WCO biodiesel and commercial diesel.

Property	**Method**	**Unit**	**Diesel (Typical)**	**WCO Biodiesel (This Study)**	**ASTM D6751 Limit**	**Remarks**
Density @ 28°C	ASTM D1298	kg/m³	832	875	860–900	Slightly higher due to oxygen content in esters
Kinematic	ASTM	mm²/s	2.6	4.6	1.9–6.0	Within

Viscosity (40°C)	D445					acceptable range
Flash Point	ASTM D93	°C	70	168	≥130	Higher — safer handling and storage
Acid Value	ASTM D664	mg KOH/g	0.05	0.36	≤0.50	Acceptable; low FFA after pretreatment
Calorific Value	ASTM D4809	MJ/kg	43.1	39.6	—	Slightly lower due to oxygenated structure
Cetane Number	ASTM D613	—	47	55	≥47	Superior ignition quality
Pour Point	ASTM D97	°C	-7	1	—	Marginally higher — expected for biodiesel

4.2. Density and Viscosity

The density of biodiesel is typically greater than that of diesel due to the presence of oxygenated methyl esters. The measured density of 875 kg/m³ aligns with findings by Meher et al. (2006) and Gui et al. (2008) , indicating proper conversion with minimal unreacted triglycerides. The kinematic viscosity value of 4.6 mm²/s is within ASTM and EN limits, confirming efficient transesterification and minimal polymeric residues. High viscosity leads to poor atomization and injector coking, while low viscosity causes insufficient lubrication. Thus, the obtained value reflects a balanced conversion of WCO to biodiesel methyl esters, similar to reported ranges for palm and jatropha biodiesel (4.2–4.8 mm²/s)

4.3. Flash Point and Safety Considerations

The flash point of biodiesel was significantly higher (168°C) than that of conventional diesel (70°C), indicating lower volatility and safer handling. Similar trends were reported by Mittelbach and Tritthar (1988) and Park et al. (2008).

The elevated flash point results from the complete removal of methanol during post-reaction purification. This property makes biodiesel favorable for storage and transport, especially in tropical climates where diesel vapors pose ignition risks.

4.4. Acid Value

The acid value measures residual free fatty acids (FFA) or degradation by-products. The obtained value (0.36 mg KOH/g) lies well below the ASTM limit of 0.50 mg KOH/g, suggesting effective pretreatment and catalyst neutralization. Elevated FFAs typically lead to soap formation during transesterification, reducing yield. The controlled acid value validates the efficiency of the pretreatment (heating and filtration) step before KOH catalysis .

4.5. Calorific Value

The calorific value of biodiesel (39.6 MJ/kg) was slightly lower than diesel (43.1 MJ/kg) due to the intrinsic oxygen atoms in methyl esters, which contribute less to combustion energy. This observation matches literature where WCO and jatropha methyl esters exhibit a 6–10% lower energy content compared to petro-diesel. Despite the lower heating value, biodiesel's higher cetane number improves ignition quality, partially compensating for this energy deficit in engine applications.

4.6. Cetane Number and Combustion Behavior

The cetane number of biodiesel was measured at 55, exceeding the ASTM minimum requirement (47). This implies shorter ignition delay and smoother combustion, consistent with prior reports on WCO-based biodiesel . High cetane values are linked to the predominance of saturated and monounsaturated fatty esters, particularly methyl oleate (C18:1), which enhance combustion stability.

4.7. Pour Point and Cold Flow Properties

The pour point of biodiesel was observed at 1°C, higher than that of diesel (-7°C), indicating a tendency for crystallization under cold conditions. Similar challenges were reported by Demirbas (2009) While not critical in tropical climates, the cold flow limitation can be mitigated through blending (B20) or the use of pour point depressants for colder regions.

4.8. Discussion on Feedstock Variability

A key novelty of this work lies in using variable WCO feedstocks from multiple sources, which introduced minor fluctuations in density (±5 kg/m³) and acid values (±0.05 mg KOH/g). This variation confirms that feedstock inconsistency marginally affects physicochemical quality but remains within international biodiesel standards. Such variability reflects the real-world condition of WCO supply chains, reinforcing the robustness of the base-catalyzed transesterification process.

4.9. Overall Assessment

All tested parameters of WCO biodiesel complied with ASTM D6751 and EN 14214 standards, proving that proper pretreatment and controlled base-catalyzed transesterification can yield fuel with desirable performance and safety characteristics. Compared to diesel, WCO biodiesel offers:

- Higher flash point → better safety,
- Comparable viscosity → reliable atomization,
- Higher cetane → smoother combustion,
- Slightly lower calorific value → marginal power drop (≈5%),
- Moderate pour point → manageable under local conditions.

5. CONCLUSION

This study successfully demonstrated the production and characterization of biodiesel from variable waste cooking oil (WCO) feedstocks through a simple base-catalyzed (KOH) transesterification process. The results confirmed that feedstock heterogeneity arising from differences in prior frying cycles, contamination, and storage only marginally affected the physicochemical properties of the produced biodiesel when proper pretreatment and reaction control were applied. The final biodiesel exhibited a density of 875 kg/m^3, viscosity of 4.6 mm^2/s, flash point of 168 °C, and calorific value of 39.6 MJ/kg, all within ASTM D6751 and EN 14214 standards. These findings indicate effective transesterification and fuel quality comparable to other published works on waste-derived biodiesel.

The study reinforces that waste cooking oil is a technically feasible and environmentally responsible raw material for biodiesel production, offering dual benefits of waste reduction and renewable energy generation. The simplicity of the process using common reagents (methanol, KOH) and basic equipment makes it suitable for small- to medium-scale decentralized production units, particularly in developing regions where used cooking oil disposal remains a persistent environmental challenge.

6. Author Contribution

The authors confirm that the work reported in this manuscript was carried out by the listed contributors. All authors made substantial contributions to the conception, design, experimentation, analysis and manuscript preparation. All authors have read and approved the final version of the manuscript for publication.

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8. Conflict of Interest

The author(s) declare that there are no conflicts of interest regarding the publication of this paper.

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