# Low-Methanol Transesterification of Used Cooking Oil: A Sustainable Route to High-Yield Fuel Oil Production

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***Abstract*—This study explores the production of fuel oil from used cooking oil (UCO) via transesterification. UCO was characterized for free fatty acids, viscosity, and density to optimize reaction conditions. For oils with high FFA, a two-step esterification and base-catalyzed transesterification was applied. Key parameters include alcohol-to-oil ratio, catalyst concentration, temperature, and time were optimized to maximize yield. The produced biodiesel met ASTM D6751 and EN 14214 standards, showing comparable fuel quality to virgin oils. Utilizing UCO provides environmental and economic benefits by converting waste into renewable fuel. This study highlights UCO as a sustainable, low-cost feedstock for biodiesel production.**

***Index Terms*— Fuel Oil, Used Cooking Oil, Transesterification, Renewable Fuel, Waste Valorization.**

## I. INTRODUCTION

The accelerating depletion of fossil fuel reserves, coupled with growing concerns over greenhouse gas emissions and environmental sustainability, has intensified global efforts to develop renewable and low-carbon energy alternatives. Fuel oil has gained significant attention as a promising substitute for petroleum diesel due to its biodegradability, non-toxicity, favorable combustion characteristics, and compatibility with existing diesel engines [1]. However, the large-scale adoption of fuel oil remains constrained by feedstock cost and process economics, which together account for a substantial portion of overall production expenses.

In this context, used cooking oil (UCO) has emerged as an attractive second-generation fuel oil feedstock owing to its low cost, widespread availability, and potential to mitigate environmental pollution arising from improper disposal. The reutilization of UCO not only reduces dependence on edible oils, thereby avoiding food–fuel conflicts, but also supports circular economy principles by converting an urban waste stream into value-added renewable fuel [2]. Nevertheless, the physicochemical complexity of UCO, particularly its elevated free fatty acid (FFA) content and moisture levels poses significant challenges during fuel oil production, necessitating careful process design and optimization.

Methanol-based transesterification remains the most widely adopted route for fuel oil production due to methanol's high reactivity, low cost, and favorable miscibility with alkaline catalysts [3]. Conventionally, excess methanol (typically ≥6:1 molar ratio relative to oil) is employed to shift the reaction equilibrium toward ester formation and achieve high conversion. While effective, this approach leads to increased operational costs associated with methanol recovery, higher energy consumption, and a larger environmental footprint. Moreover, excessive methanol adversely affects glycerol separation, complicates downstream purification, and diminishes the overall sustainability of the process. Despite its industrial prevalence, methanol usage itself has received limited critical attention from a process minimization and sustainability perspective, particularly in the context of UCO-derived fuel oil.

Recent studies have largely focused on catalyst development, alternative alcohols, or process intensification techniques [4], while the fundamental question of how low methanol consumption can be reduced without compromising fuel oil yield and quality remains insufficiently addressed. Achieving high conversion at reduced methanol-to-oil ratios is especially challenging when processing UCO [5], due to its inherent heterogeneity and FFA content. Consequently, there exists a clear research gap in developing a low-methanol transesterification strategy that balances reaction efficiency, product quality, and process sustainability.

Addressing this gap is crucial from both economic and environmental standpoints. Reducing methanol consumption directly lowers raw material costs, decreases energy demand for alcohol recovery, minimizes wastewater generation, and improves glycerol purity, factors that collectively enhance process viability at an industrial scale. Furthermore, a low-methanol approach aligns fuel oil production with green chemistry principles and strengthens its position as a truly sustainable fuel alternative.

In light of these considerations, the present study aims to develop and optimize a low-methanol transesterification process for fuel oil production from used cooking oil, focusing on achieving high yield under reduced alcohol usage. Process parameters influencing conversion efficiency are systematically evaluated, and the optimized conditions are validated through statistical modeling and fuel property characterization. The quality of the produced fuel oil is assessed against relevant international standards to ensure its suitability for practical application. By demonstrating high-yield fuel oil production under low methanol conditions, this work provides a sustainable and industrially relevant pathway for valorizing used cooking oil into renewable fuel.

## II. MATERIALS AND METHODS

### *A. Materials*

Used cooking oil (UCO) was collected from local food establishments and filtered to remove food residues and suspended impurities. Analytical-grade methanol (≥99.8% purity), sodium hydroxide (NaOH), potassium hydroxide (KOH), sulfuric acid ($H_2SO_4$), and all other reagents were procured from standard chemical suppliers and used without further purification. Distilled water was employed for washing and analytical procedures.

### *B. Pretreatment and Characterization of Used Cooking Oil*

The collected UCO was first heated to 105 °C for 30 min to remove residual moisture and then allowed to cool to room temperature. The free fatty acid (FFA) content of the oil was determined by acid–base titration using potassium hydroxide, following standard procedures. Based on the measured FFA value, appropriate pretreatment strategies were adopted to minimize soap formation during transesterification.

### *C. Low-Methanol Transesterification Process*

Base-catalyzed transesterification was performed using methanol under reduced methanol-to-oil molar ratios, emphasizing process sustainability. Sodium hydroxide or potassium hydroxide was dissolved in methanol to prepare the catalyst solution, which was then added to the pretreated oil in a temperature-controlled batch reactor.

The reaction was conducted at temperatures ranging from 50 to 65°C with continuous stirring. Key process variables including methanol-to-oil molar ratio, catalyst loading, reaction temperature, and reaction time were systematically varied according to the experimental design. Upon completion of the reaction, the mixture was transferred to a separating funnel and allowed to settle under gravity to facilitate phase separation between fuel oil and glycerol.

### *D. Determination of Fuel oil Yield*

Fuel oil yield was calculated based on the mass of purified fuel oil obtained relative to the initial mass of oil used, as expressed by:

$$\text{Fuel oil Yield (\%)} = \frac{Mass\ of\ fuel\ oil\ Produced}{Mass\ of\ oil\ used} x\ 100$$

### *E. Fuel Property Characterization*

The physicochemical properties of the produced fuel oil were analyzed in accordance with relevant ASTM and EN standards. Key properties evaluated included density, kinematic viscosity, flash point, calorific value, acid value, and ester content. The measured properties were compared with international fuel oil specifications (ASTM D6751 and EN 14214) to assess fuel quality and suitability for diesel engine applications [6].

### *F. FTIR Spectroscopic Analysis*

Fourier Transform Infrared (FTIR) spectroscopy was employed to characterize the functional groups and chemical constituents present in the fuel oil [7]. FTIR analysis was performed using an FT-IR spectrometer (Cary 630 FTIR with Diamond ATR from Agilent

Technologies, USA) operating in the mid-infrared region of 4000–600 $cm^{-1}$.

Prior to analysis, the fuel oil sample was brought to room temperature and homogenized gently. A small aliquot of the sample was placed directly on the ATR crystal/sample holder, and spectra were recorded at room temperature with an appropriate number of scans to improve signal-to-noise ratio. The obtained spectra were analyzed to identify characteristic functional groups present in the produced.

## III. RESULTS AND DISCUSSION

### *A. Fuel Property Characterization*

The physicochemical properties of the fuel oil produced under optimized low-methanol transesterification conditions were evaluated and compared with international fuel oil standards (ASTM D6751 and EN 14214) to assess fuel quality and applicability [8] as summarized in Table 1.

The density of the produced fuel oil was measured as 872 kg $m^{-3}$ at 28°C, which falls well within the EN 14214 specified range of 860–900 kg $m^{-3}$. This density range ensures proper fuel injection characteristics and effective atomization in diesel engines [9].

The kinematic viscosity, determined at 40°C, was found to be 4.52 $mm^2$ $s^{-1}$, complying with both ASTM D6751 (1.9–6.0 $mm^2$ $s^{-1}$) and EN 14214 (3.5–5.0 $mm^2$ $s^{-1}$) standards. The significant reduction in viscosity compared to raw used cooking oil confirms efficient conversion of triglycerides into fatty acid methyl esters, even under reduced methanol usage [10].

The flash point of the fuel oil was recorded as 168 °C, which is substantially higher than the minimum requirement of 130 °C (ASTM D6751). This high flash point indicates effective removal of residual methanol during purification and highlights the improved safety of the produced fuel oil during storage and handling.

The calorific value of the fuel oil was measured as 39.8 MJ $kg^{-1}$, slightly lower than conventional petroleum diesel but within the typical range reported for fatty acid methyl esters. This value confirms that the energy content of the fuel oil remains sufficient for practical engine operation without significant loss in performance [11].

The acid value of the produced fuel oil was determined to be 0.38 mg KOH $g^{-1}$, well below the maximum allowable limit of 0.50 mg KOH $g^{-1}$ specified by ASTM and EN standards. The low acid value reflects effective pre-treatment of the used cooking oil and minimal free fatty acid presence in the final fuel, which is essential for preventing corrosion and deposit formation in engine components [12].

The ester content, calculated according to EN 14103, was found to be 97.6 wt%, exceeding the EN 14214 minimum requirement of 96.5 wt%. This high ester content confirms near-complete transesterification and validates the effectiveness of the optimized low-methanol process [13].

Table 1 Properties of Fuel Oil

| Parameter | Value |
|---|---|
| Density (28°C) | 872 kg $m^{-3}$ |
| Kinematic viscosity (40°C) | 4.52 $mm^2$ $s^{-1}$ |
| Flash point | 168°C |
| Calorific value | 39.8 MJ $kg^{-1}$ |
| Acid value | 0.38 mg KOH $g^{-1}$ |
| Ester content | 97.6 wt% |
| Yield | 83.4% |

### *B. FTIR Spectral Interpretation of Fuel Oil*

The FTIR spectrum of the fuel produced from used cooking oil under optimized low-methanol transesterification conditions confirms the successful formation of fatty acid methyl esters. As shown in Figure 1, the prominent absorption bands at 2918 $cm^{-1}$ and 2851 $cm^{-1}$ correspond to asymmetric and symmetric stretching vibrations of aliphatic $–CH_2$ groups, indicating long hydrocarbon chains typical of biodiesel. The sharp and intense peak observed at 1740.7 $cm^{-1}$ is attributed to the ester carbonyl (C=O) stretching vibration, serving as a definitive signature of methyl ester formation.

The band at 1654.9 $cm^{-1}$ is associated with C=C stretching of unsaturated fatty acid chains, while the peak at 1461.1 $cm^{-1}$ corresponds to $–CH_2$ bending vibrations. Strong absorption bands in the region of 1244–1114 $cm^{-1}$ are characteristic of C–O–C stretching vibrations of ester linkages, further confirming transesterification. The absence of a broad O–H

stretching band indicates effective removal of glycerol and unreacted methanol during purification [14].

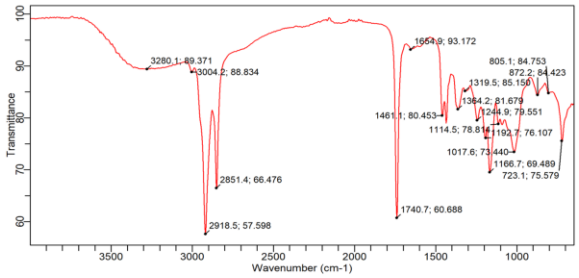


Fig. 1 FTIR Graph of Fuel Oil

## IV. CONCLUSIONS

This study demonstrates the successful production of high-quality biodiesel from used cooking oil through a low-methanol transesterification approach, achieving a high biodiesel yield while significantly reducing alcohol consumption compared to conventional methods. Optimization of key process parameters enabled efficient conversion under reduced methanol-to-oil ratios without compromising phase separation or fuel quality. FTIR analysis confirmed the formation of fatty acid methyl esters, and the physicochemical properties of the produced biodiesel complied with international standards, validating its suitability as a diesel substitute. By minimizing methanol usage, the developed process lowers raw material demand, reduces downstream purification requirements, and enhances overall process sustainability. The findings highlight the potential of low-methanol transesterification as an economically and environmentally viable pathway for the large-scale valorization of used cooking oil into renewable biodiesel.

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