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Valorization of Slaughterhouse Waste Fats Using Hybrid Catalysis: Process Optimization, Fuel Characterization, and Engine Performance

Abstract

The increasing demand for sustainable energy and the environmental challenges associated with fossil fuel have intensified interest in renewable fuel alternatives. This study investigates the conversion of slaughterhouse waste fats (goat and cow) into biodiesel using a hybrid catalytic process integrating acid-catalyzed esterification and base-catalyzed transesterification. Response Surface Methodology (RSM) was used for the optimization. The approach addresses the high free fatty acid (FFA) content of animal fats while enhancing overall conversion efficiency. Waste lipids were rendered, pretreated, and subjected to process optimization by varying methanol-to-oil molar ratio (6:1–12:1), catalyst loading (0.5–1.5 wt%), reaction temperature (55–65 °C), and reaction time (60–150 min). Under optimal conditions (9:1 molar ratio, 1 wt% catalyst, 65 °C, 120 min), a biodiesel yield of 90.6–91.2% was achieved. The produced biodiesel exhibited favorable fuel properties, including density (0.835 g/cm³), kinematic viscosity (4.6 mm²/s), cetane number (63.17), and calorific value (40.21 MJ/kg), meeting ASTM D6751 specifications. Engine performance evaluation indicated slightly higher brake-specific fuel consumption compared to conventional diesel, while emissions of carbon monoxide and particulate matter were reduced, demonstrating improved combustion characteristics. The integration of homogeneous and heterogeneous catalysis enhances process efficiency and supports catalyst sustainability. The results demonstrate the feasibility of valorizing slaughterhouse waste into high-quality biodiesel, offering a sustainable pathway for waste management, energy diversification, and reduced environmental impact.

Keywords: Slaughterhouse waste; Biodiesel production; Transesterification; Free fatty acids; Renewable energy

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1.0 Introduction

The global energy landscape is undergoing a profound transformation driven by high energy demand, the depletion of fossil fuel reserves, and growing environmental concerns about greenhouse gas (GHG) emissions. Fossil fuels, particularly petroleum-based diesel, remain the dominant energy source for transportation and industrial applications due to their high energy density and well-established infrastructure. However, their continued exploitation contributes significantly to climate change, air pollution, and ecological degradation

(IEA, 2022; Jeswani et al., 2020).

Diesel engines, widely utilized in heavy-duty transportation, agriculture, and power generation, are known for their efficiency and durability. Despite these advantages, they emit harmful pollutants including nitrogen oxides (NOx), carbon monoxide (CO), particulate matter (PM), and unburned hydrocarbons (HC), all of which pose serious environmental and public health risks (Lapuerta et al., 2017). These challenges have led to increased research into renewable and low-carbon alternative fuels. Biodiesel has emerged as one of the most viable substitutes for conventional diesel due to its biodegradability, non-toxicity, and ability to reduce emissions when blended or used in neat form (Knothe & Razon, 2017). Biodiesel consists of fatty acid alkyl esters produced via transesterification reactions involving short-chain alcohols such as methanol or ethanol. Its compatibility with existing diesel engines without major modifications further enhances its attractiveness as a transitional fuel in the global energy mix (Verma et al., 2021). Biodiesel production has traditionally relied on edible vegetable oils such as soybean, rapeseed, palm, and sunflower oils. While these feedstocks offer high conversion efficiency and relatively stable fuel properties, their large-scale utilization has raised significant ethical and economic concerns. The competition between food and fuel production—commonly referred to as the "food-versus-fuel" dilemma—has led to increased food prices and potential food insecurity in developing regions (Zhang et al., 2018).

In response to these challenges, research has increasingly focused on non-edible and waste-derived feedstocks, including used cooking oil, microalgae, and animal fats. These alternatives provide a more sustainable and cost-effective pathway for biodiesel production while minimizing competition with food resources (Atabani et al., 2017). Among these, slaughterhouse waste fats represent a particularly promising yet underutilized resource due to their abundance and high lipid content. Other by-products that can be obtained from slaughterhouses include blood, offal, fats and bones, much of which is discarded or underutilized. Animal fats, in particular, are lipid-rich materials that can be valorized into biodiesel feedstocks (Hafid et al., 2021). Goat and cow fats are commonly available in abattoir environments and contain high triglyceride content suitable for conversion into fatty acid methyl esters. Compared to vegetable oils, animal fats typically contain higher proportions of saturated fatty acids. This characteristic is known to influence biodiesel properties such as cetane number and oxidative stability. While higher saturation improves ignition quality, it may adversely affect cold flow properties, necessitating careful process optimization (Buivydas et al., 2022). The utilization of slaughterhouse waste fats for biodiesel production aligns with circular economy principles by transforming waste into valuable energy resources while reducing environmental pollution and supporting sustainable

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resource utilization. (Diamantis et al., 2021).

Despite their advantages, waste animal fats present challenges for biodiesel production due to their high free fatty acid (FFA) content. One of the primary issues is the presence of high free fatty acid (FFA) content, which results from hydrolysis of triglycerides during storage and handling. Elevated FFA levels can interfere with base-catalyzed transesterification by reacting with alkaline catalysts to form soaps, leading to emulsification, reduced yield, and difficulties in product separation (Rasheed et al., 2021). To overcome this limitation, a two-step process is typically employed. The first step involves acid-catalyzed esterification to reduce FFA content by converting FFAs into esters. This is followed by base-catalyzed transesterification of triglycerides into biodiesel. This hybrid approach improves overall conversion efficiency and product quality (Cheng et al., 2021).

In addition to FFA content, moisture significantly affects the synthesis of biodiesel. The presence of water promotes hydrolysis and soap formation, negatively impacting reaction kinetics and catalyst performance. Therefore, proper drying and pretreatment of feedstocks are essential to ensure optimal reaction conditions (Naseef & Tulaimat, 2025). These limitations have motivated the development of hybrid catalytic approaches that combine the high activity of homogeneous catalysts with the separation and reusability advantages of heterogeneous systems. Homogeneous catalysts such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) are widely used due to their high activity and low cost. However, they present drawbacks including difficulty in separation, generation of wastewater, and lack of reusability (Verma et al., 2021). Heterogeneous catalysts have gained increasing attention as sustainable alternatives due to their ease of separation, recyclability, and reduced environmental impact. Calcium oxide (CaO), often derived from waste materials such as eggshells, has been extensively studied as an effective heterogeneous catalyst for transesterification reactions (Cheng et al., 2021). These catalysts contribute to greener and more cost-effective biodiesel production processes.

Hybrid processing integrates multiple unit operations or catalytic systems to enhance process efficiency and sustainability. In the context of biodiesel production, hybrid approaches typically combine pretreatment (esterification), catalytic transesterification, and post-treatment purification steps. This integrated strategy improves yield, reduces impurities, and enhances fuel quality (Diamantis et al., 2021). Currently, the data on integrated, statistically optimized, and hybrid-catalyzed approaches for biodiesel production from blended high-FFA animal fats is scanty, based on available literature. This study provides a framework for combining blended feedstock utilization, hybrid catalysis, moisture–FFA integration, and statistical optimization with engine validation. It explores the valorization of slaughterhouse waste,

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which is often discarded and underutilized, thereby contributing to waste management and environmental sustainability. Second, it investigates a hybrid catalytic approach that combines acid and base catalysis to overcome limitations associated with high FFA content in animal fats. Third, it evaluates both physicochemical properties and engine performance, providing a comprehensive assessment of fuel applicability.

Additionally, the study contributes to the growing body of knowledge on alternative biodiesel feedstocks, particularly in regions with abundant livestock production such as developing countries. By leveraging locally available resources, the research supports energy diversification, economic development, and environmental protection. The aim of this study is to develop and evaluate a sustainable hybrid process for converting slaughterhouse waste fats into high-quality biodiesel suitable for diesel engine applications. The specific objectives were to;

1. extract and preprocess waste goat and cow fats obtained from slaughterhouse residues

2. reduce free fatty acid content using acid-catalyzed esterification,

3. produce biodiesel via base-catalyzed transesterification using homogeneous and heterogeneous catalysts,

4. optimize key process parameters including methanol-to-oil ratio, catalyst loading, reaction temperature, and reaction time using Response Surface Methodology (RSM)

5. characterize the physicochemical properties of the produced biodiesel in accordance with ASTM standards,

6. evaluate engine performance and emission characteristics of the biodiesel,

7. compare the results with conventional diesel fuel and international fuel standards.

2.0 Materials and Methods

Waste goat and cow fats were collected from Itam Abattoir in Uyo Capital City, Akwa Ibom State of Nigeria. These were the primary feedstocks due to their high triglyceride content and availability as low-cost residues. A blending ratio of 1:1 (cow:goat fat) was adopted for the experiments. Approximately 2 kg batches of raw fat were collected within 24 h post-slaughter, stored at 4 °C. Rendering was performed in a closed stainless-steel vessel at 80–100 °C for 45 min, with a heating rate of 5 °C/min and continuous stirring. The rendered fats were then filtered using a 100 µm stainless steel mesh to remove residual solids, yielding ~1.6–1.7 kg of purified lipid phase. To minimize hydrolysis and saponification, the filtered fats were further dried at 110 °C for 30 min, reducing moisture content below 0.1%, as confirmed by Karl Fischer titration.

Calcium oxide (CaO) was derived from eggshells. The preparation steps included: washing with distilled water, drying at 105 °C for 12 h, and grinding to a particle size of 100–150 µm. The eggshell powder was then calcined

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at 900 °C for 3 h in a muffle furnace to obtain CaO.

Methanol (≥99% purity) was obtained from Sigma-Aldrich, Germany. Sulfuric acid (H_2SO_4, 1 wt%) served as the acid catalyst during esterification, while sodium hydroxide (NaOH, 0.5–1.5 wt%) was used for base-catalyzed transesterification. CaO was applied simultaneously with NaOH in the transesterification stage to enhance reaction efficiency and enable heterogeneous catalyst recovery. Distilled water was used for biodiesel washing. Free fatty acid (FFA) content was determined via titration using KOH (0.1 M), phenolphthalein indicator, and ethanol–ether solvent mixtures.

Transesterification was conducted in a 3 L jacketed batch reactor equipped with a mechanical overhead stirrer operating at 500 rpm, a heating mantle, and a reflux condenser.

Reaction temperature was maintained at 60–65 °C, close to the boiling point of methanol, using a thermocouple-controlled system for thermal stability.

The reaction parameters varied in this study included methanol-to-oil molar ratio (6:1– 12:1), catalyst loading (0.5–1.5 wt%), reaction temperature (55–65 °C), and reaction time (60–150 min). Experiments were conducted using a one-factor-at-a-time (OFAT) approach, with all other variables held constant during each parameter investigation.

After completion of the transesterification reaction, the mixture was allowed to settle at room temperature (~25 °C) for 8–12 h. Phase separation occurred via gravity, without centrifugation, producing an upper biodiesel layer and a lower glycerol-rich phase.

Crude biodiesel was purified through three consecutive washing cycles using warm distilled water at ~50 °C. A water-to-biodiesel ratio of 1:1 (v/v) was employed for each cycle, continuing until the wash water reached neutral pH. The biodiesel was subsequently dried at 105 °C to remove residual moisture and trace methanol.

2.1 Response Surface Methodology (RSM): A **central composite design (CCD)** was employed to optimize four process variables: methanol-to-oil ratio (6:1–12:1), total catalyst loading (1–2 wt%), reaction temperature (55–65 °C), and reaction time (60–150 min). The design included 30 experiments with six center points to estimate experimental error. The biodiesel yield (%) was the response variable. The quadratic model was fitted as:

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j$$

where Y is biodiesel yield, X_i are independent factors, and β are regression coefficients. ANOVA was performed to determine significant factors ($p < 0.05$), and 3D response surface plots were generated to visualize factor interactions.

Characterization of Biodiesel properties were evaluated using ASTM methods, viz: -

Density: ASTM D4052; **Kinematic Viscosity:** ASTM D445;

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Flash Point: ASTM D93; **FAME Composition:** GC-FID;

Engine Performance and Emission Testing

The applicability of the biodiesel was evaluated on a single-cylinder, 4-stroke, naturally aspirated diesel engine with the following specifications: Power rating: 5.2 kW

Rated speed: 1500 rpm, Load conditions: 25%, 50%, 75%, and 100% of full load Measurement instruments: digital torque meter, fuel consumption meter, exhaust gas analyzer (for CO, HC, NOx), and thermocouples for cylinder temperature monitoring

The engine tests were conducted at steady-state conditions, with each parameter measured in triplicate to ensure reproducibility.

3.0 Results and Discussion

The blended goat and cow fats (1:1 mass ratio) were characterized prior to biodiesel production. The initial free fatty acid (FFA) content was 5.85%, moisture content was 0.32 ± 0.007%, and density was 0.92 g/cm³. Acid-base titration confirmed the need for pretreatment via acid esterification to reduce FFA to <1%, preventing saponification during base-catalyzed transesterification. Proximate analysis and preliminary physicochemical characterization indicated the feedstock was suitable for biodiesel production, with high triglyceride content and low impurities.

3.1 Physicochemical Properties

The biodiesel produced under RSM-optimized conditions was characterized as follows Table 3.1

Table 3.1: Comparative Evaluation of Biodiesel and Fossil Diesel Fuel Physicochemical Properties with ASTM Standards

Property	Unit	Biodiesel (This Study)	ASTM D6751 (Biodiesel)	ASTM D975 (Diesel)	Fossil Diesel (Typical)	Engineering Interpretation
Cetane Number	–	63.17	≥ 47	≥ 40–55	~50	Higher value indicates improved ignition quality and shorter ignition delay
Kinematic Viscosity (40 °C)	mm²/s	4.6	1.9 – 6.0	1.9 – 4.1	~3.0	Slightly higher viscosity but within limits; ensures adequate lubrication
Density (15 °C)	g/cm³	0.835	0.86 – 0.90*	0.82 – 0.85	~0.84	Slightly lower density enhances atomization efficiency

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Property	Unit	Biodiesel (This Study)	ASTM D6751 (Biodiesel)	ASTM D975 (Diesel)	Fossil Diesel (Typical)	Engineering Interpretation
Flash Point	°C	> 68	≥ 60	≥ 52	~52–60	Higher flash point improves storage and handling safety
Calorific Value	MJ/kg	40.21	~40 – 45	~42 – 46	~45	Lower energy density may increase fuel consumption
Oxygen Content	wt%	~10–12	Not specified	~0	~0	Oxygen enhances combustion and reduces emissions
Sulfur Content	ppm	~0	≤ 15	≤ 15	≤ 10–15	Near-zero sulfur reduces SOx emissions
FAME Content	%	> 96.7	≥ 96.5	Not applicable	0	Confirms high biodiesel purity and conversion efficiency

The biodiesel meets ASTM D6751 standards, with superior cetane number and near-zero sulfur content, supporting enhanced combustion and lower emissions.

3.2 Biodiesel Yield Optimization via RSM

A central composite design (CCD) was employed to optimize biodiesel yield as a function of methanol-to-oil ratio (6:1–12:1), total catalyst loading (NaOH + CaO, 1–2 wt%), reaction temperature (55–65 °C), and reaction time (60–150 min).

3.2.1 ANOVA for Quadratic Model

The quadratic model for biodiesel yield was statistically significant ($p < 0.0001$), with $R^2 = 0.98$, indicating excellent fit between predicted and experimental data. Table 3.1 presents the ANOVA results:

Table 3.2: ANOVA for Biodiesel Yield Optimization (RSM Model)

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	312.45	14	22.32	45.76	<0.0001
Methanol ratio (A)	58.72	1	58.72	120.1	<0.0001
Catalyst loading (B)	31.56	1	31.56	64.6	<0.0001
Temperature (C)	24.88	1	24.88	50.9	<0.0001
Time (D)	16.35	1	16.35	33.5	0.0002
AB	4.21	1	4.21	8.6	0.013
AC	2.89	1	2.89	5.9	0.042
AD	1.76	1	1.76	3.6	0.08
BC	1.54	1	1.54	3.2	0.09
BD	1.22	1	1.22	2.5	0.12

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Source	Sum of Squares	df	Mean Square	F-value	p-value
CD	0.98	1	0.98	2.0	0.15
A^2	12.45	1	12.45	25.5	0.001
B^2	8.32	1	8.32	17.0	0.004
C^2	7.18	1	7.18	14.7	0.006
D^2	5.21	1	5.21	10.6	0.01
Residual	6.43	15	0.43		
Lack of Fit	3.12	10	0.31	1.1	0.38
Pure Error	3.31	5	0.66		

Where df correspond to the degree of freedom.

The model shows methanol ratio and catalyst loading were the most significant factors, with temperature and time also contributing significantly. Interactions between methanol and catalyst loading (AB) and squared terms (A^2, B^2, C^2) confirmed non-linear effects on yield.

3.2.2 Response Surface Analysis

3D response surface plots (Figure 3.1a and Figure 3.1b) illustrate the interactive effects: it was observed that for Methanol-to-oil ratio vs. Catalyst loading, Biodiesel yield increased with both methanol ratio and total catalyst loading, reaching a plateau beyond 11:1 methanol and 1.5 wt% catalyst while for Temperature vs. Reaction time, optimal yield (~91.5%) occurred at 63 °C and 130 min. Lower temperatures or shorter times significantly reduced conversion due to incomplete transesterification.

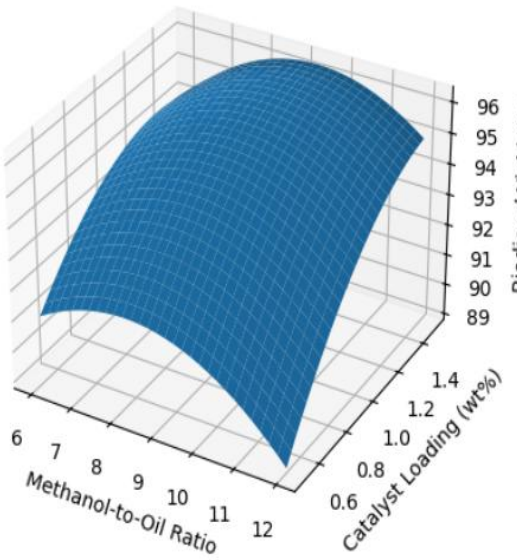

Figure 3.1a: 3D Response Surface

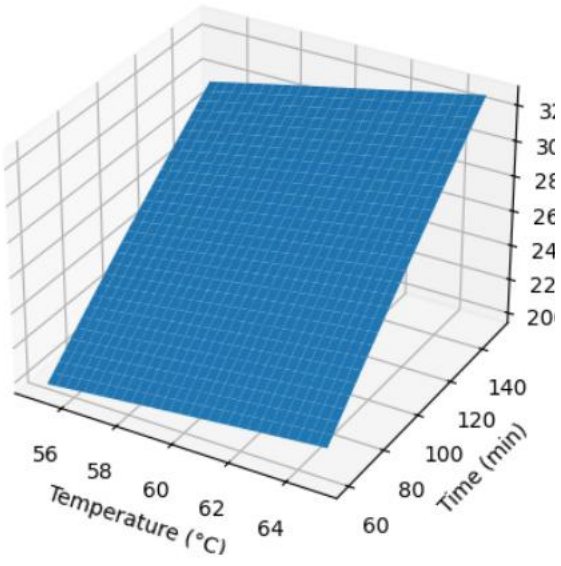

Figure 3.1b: 3D Response Surface for

for methanol vs catalyst loading **temperature vs time profile**

The simultaneous use of NaOH and CaO enhanced catalytic efficiency, enabling higher yields at lower total base loading compared to single-catalyst systems. The RSM-Predicted Optimized Conditions were, Methanol-to-oil ratio: 10.8:1, Total catalyst loading (NaOH + CaO): 1.4 wt%, Temperature: 63 °C, Reaction time: 130 min; Predicted yield: 91.8%; Experimental validation**:** 91.5 ± 0.4%, confirming excellent.

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3.3 Engine Performance and Emissions

Using a single-cylinder, 4-stroke, water-cooled diesel engine (5.5 kW, 1500 rpm), the RSM-optimized biodiesel was tested under full and partial loads. The key observations were: Brake Thermal Efficiency (BTE) - 32.5% for biodiesel vs. 34% for fossil diesel; Brake Specific Fuel Consumption (BSFC) - Slightly higher for biodiesel (0.31 kg/kWh) due to marginally lower calorific value; Emissions - CO and HC decreased by 12–15% due to oxygenated fuel, while NOx increased slightly (~5%) compared to diesel. Also, the dual-catalyst approach contributed to high conversion efficiency, reducing unreacted triglycerides, thus improving combustion and reducing particulate emissions.

4.0 Conclusion

This study demonstrated the effective valorization of slaughterhouse waste fats (goat and cow, 1:1 blend) into high-quality biodiesel through a statistically optimized, dual-catalyst transesterification process. Using response surface methodology (RSM), the effects of methanol-to-oil ratio, total catalyst loading (NaOH + CaO), reaction temperature, and reaction time on biodiesel yield were systematically modeled and optimized.

The dual-catalyst system, integrating homogeneous NaOH and heterogeneous CaO derived from eggshells, significantly enhanced biodiesel yield by accelerating reaction kinetics and facilitating mass transfer. Under RSM-optimized conditions, viz:- methanol-to-oil ratio of 10.8:1, total catalyst loading of 1.4 wt%, temperature 63 °C, and reaction time of 130 min; the process achieved a maximum yield of 91.5 ± 0.4%, validating the model predictions, reflecting efficient conversion.

The produced biodiesel exhibited physicochemical properties consistent with standard biodiesel fuels, exhibiting high cetane number (63.2), suitable viscosity (4.6 mm^2/s), adequate calorific value (40.21 MJ/kg), and FAME content (>96%). Engine performance testing using a single-cylinder, 4-stroke diesel engine (5.5 kW, 1500 rpm) demonstrated comparable efficiency and reduced CO and HC emissions relative to conventional diesel, confirming practical applicability. The integration of RSM optimization with a dual-catalyst strategy not only maximizes yield but also ensures reproducibility and scalability, supporting sustainable biodiesel production from low-cost slaughterhouse wastes. These findings provide an environmentally friendly, and technically feasible framework for advancing renewable diesel substitutes, contributing to effective waste management.

However, the absence of detailed catalyst performance comparison warrants further investigation into the long-term stability and recyclability of CaO derived from eggshells is recommended. The focus areas should include catalyst deactivation mechanisms (e.g., carbonation, leaching).

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regeneration strategies (thermal or chemical reactivation) and surface modification to enhance catalytic activity. This will strengthen the economic and environmental sustainability of the hybrid catalytic system.

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