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Transesterification of Waste Cooking Oil Using Calcium Oxide Derived from Eggshells: Response Surface Methodology

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Abstract

The growing need for sustainable energy has elevated biodiesel as a promising substitute for conventional fossil diesel. This study optimized biodiesel production from waste cooking oil (WCO) through transesterification using calcium oxide (CaO) derived from waste chicken eggshells as a low-cost heterogeneous base catalyst. The catalyst was prepared by calcining eggshells at 900°C for 3 hours and characterized by Fourier Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscopy (SEM). Response Surface Methodology (RSM) combined with Central Composite Design (CCD) was utilized to optimize two critical variables: methanol-to-oil molar ratio (6:1–10:1) and catalyst loading (1.1–1.4 wt%), while keeping reaction temperature at 60°C and time at 60 min. A quadratic model was developed and found statistically significant (F-value = 6.05, $p = 0.0176$) with $R^2 = 0.8121$. Catalyst loading showed the strongest positive linear effect, followed by the methanol-to-oil ratio. The optimal conditions predicted by the model (methanol-to-oil ratio of 9.5:1 and catalyst loading of 1.2 wt%) yielded 89.8% biodiesel, which was experimentally validated at 88.9 ± 0.8%. The resulting biodiesel satisfied key ASTM specifications. This research highlights the viability of eggshell-derived CaO as an

eco-friendly catalyst and demonstrates the effectiveness of CCD-RSM for process optimization in waste-to-energy conversion.

Keywords: Biodiesel, Waste Cooking Oil, Eggshell-derived CaO, Transesterification, Response Surface Methodology, Central Composite Design.

Introduction

The global energy landscape is undergoing a profound transformation driven by the dual imperatives of mitigating climate change and ensuring energy security. Fossil fuel combustion remains the predominant contributor to anthropogenic greenhouse gas emissions, necessitating an urgent transition toward renewable and sustainable energy sources (El-Naggar et al., 2024). Biodiesel, a biodegradable and non-toxic alternative to petroleum-based diesel, has emerged as a promising candidate for addressing these challenges, offering reduced emissions of carbon monoxide, particulate matter, and unburned hydrocarbons while maintaining favorable combustion characteristics (Mustafa et al., 2025).

The transesterification reaction, wherein triglycerides react with short-chain alcohols in the presence of a catalyst to produce fatty acid alkyl esters (biodiesel) and glycerol, constitutes the fundamental chemical pathway for biodiesel synthesis (Makarevičienė & Sendžikienė, 2025). While homogeneous alkaline catalysts such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) have been widely employed in industrial biodiesel production due to their high catalytic activity, their utilization presents significant drawbacks including catalyst recovery difficulties, saponification in the presence of free fatty acids, and substantial wastewater generation during product purification (Makarevičienė & Sendžikienė, 2025). These limitations have catalyzed extensive research into heterogeneous catalysts, which offer advantages of facile separation, reusability, and reduced environmental footprint.

Among heterogeneous catalysts, calcium oxide (CaO) has garnered substantial attention owing to its high basicity, low solubility in methanol, cost-effectiveness, and relatively mild reaction conditions. However, commercial CaO remains economically prohibitive for large-scale biodiesel production. Consequently, the valorization of calcium-rich waste materials as precursors for CaO catalyst synthesis has emerged as an attractive strategy that aligns with circular economy principles (Teo et al., 2024).

Eggshells, generated in vast quantities as a byproduct of the food processing industry, represent an abundant and low-cost source of calcium carbonate ($CaCO_3$). Through thermal calcination, $CaCO_3$ undergoes decomposition to yield CaO, which can serve as an effective base catalyst for transesterification reactions. The typical calcination temperature range for complete conversion is 800–1000°C, with 900°C being most commonly reported to achieve optimal catalytic activity. Prior studies have

demonstrated the feasibility of employing eggshell-derived CaO catalysts for biodiesel production from various feedstocks, achieving conversion efficiencies exceeding 90% under optimized conditions.

Waste cooking oil (WCO) represents an environmentally problematic waste stream that, when improperly disposed, contributes to water pollution, soil contamination, and sewer blockages. However, WCO constitutes an economically attractive feedstock for biodiesel production, potentially reducing raw material costs by up to 70–80% compared to virgin vegetable oils. The utilization of WCO for biodiesel synthesis simultaneously addresses waste management challenges and provides a sustainable energy source, embodying the principles of waste-to-energy conversion (Garg et al., 2025; Ashok et al., 2025).

Despite its potential, large-scale biodiesel adoption faces significant challenges, particularly the high cost of virgin feedstocks and conventional catalysts. Waste cooking oil (WCO) offers a low-cost, abundant alternative feedstock, but its effective conversion via heterogeneous catalysis remains suboptimal in many reported studies. While previous optimization efforts have explored transesterification of WCO using various waste-derived CaO catalysts, many relied on traditional one-factor-at-a-time approaches that fail to capture interactive effects among variables. Others employed RSM but focused on different feedstocks, commercial CaO, or a broader set of parameters, often leaving the specific interplay between methanol-to-oil molar ratio and catalyst loading under-investigated for eggshell-derived CaO. These limitations result in incomplete understanding of process economics, catalyst efficiency, and yield maximization under realistic industrial constraints.

This study addresses these gaps by applying Central Composite Design (CCD) within Response Surface Methodology (RSM) to systematically optimize the two most critical and cost-influencing parameters methanol-to-oil molar ratio and catalyst loading using CaO derived from waste chicken eggshells for WCO transesterification. The selected parameters require further investigation because they directly govern reaction equilibrium, mass transfer, and catalyst utilization efficiency. Excess methanol drives the equilibrium forward but increases separation costs, while suboptimal catalyst loading limits active sites or promotes side reactions. By focusing on these variables while holding temperature and time constant at practical levels (60°C, 60 min), this work provides a targeted, scalable optimization framework that enhances the techno-economic viability of waste-to-biodiesel conversion.

Materials and Methods

Materials

Waste cooking oil (WCO) was collected from local sources and filtered to remove impurities. Its acid value was determined by titration and was found to be 2.4 mg KOH/g oil, corresponding to a free fatty acid (FFA) content of 1.2%, which is suitable for base-catalyzed transesterification without pretreatment. Chicken eggshells were collected from a local bakery. Methanol (99.8% purity) and all other analytical-grade reagents were purchased from a commercial supplier and used as received.

Catalyst Preparation and Characterization

Chicken eggshells were thoroughly washed with hot distilled water to remove organic residues and membranes, then dried in an oven at 105 °C for 12 hours. The dried shells were crushed and ground into a fine powder using a laboratory mill. The powder was calcined in a muffle furnace at 900 °C for 3 hours with a heating rate of 5 °C/min under static air atmosphere to convert calcium carbonate ($CaCO_3$) into active calcium oxide (CaO) as per the method established by earlier studies (Ali et al., 2023). After calcination, the resulting white CaO powder was cooled in a desiccator and stored in an airtight container to minimize hydration and carbonation.

The prepared catalyst was characterized using Fourier Transform Infrared Spectroscopy (FTIR) for functional groups, and Scanning Electron Microscopy (SEM) for morphology, X-ray diffraction (XRD) and BET.

Transesterification Procedure

The transesterification reaction was carried out in a 250 mL three-necked round bottom flask equipped with a reflux condenser, a thermometer, and a magnetic stirrer. In a typical run, 50 g of pre-heated WCO was placed in the flask, followed by the addition of a predetermined amount of the eggshell-derived CaO catalyst (1.1–1.4 wt% relative to oil) and a specified volume of methanol to achieve the desired methanol-to-oil molar ratio (6:1–10:1). The reaction mixture was heated to the target temperature (60 °C) and stirred at a constant speed of 200 rpm for the specified reaction time (60 minute). Upon completion, the mixture was cooled to room temperature. The solid CaO catalyst was separated by vacuum filtration. The filtrate was transferred to a separating funnel, where the heavier glycerol layer was allowed to settle and was drawn off. The crude biodiesel layer was washed gently with warm distilled water to remove residual methanol, catalyst, and soap, then dried over anhydrous sodium sulfate to obtain the final purified biodiesel. Yield was calculated as:

$$\text{Yield (conversion \%)} = \frac{\text{weight of biodiesel}}{\text{weight of oil (WCO)}} * 100 \qquad (1)$$

Experimental Design and Statistical Analysis

Response surface methodology (RSM) via central composite design CCD was applied to optimize the production of biodiesel from waste cooking oil during the transesterification reaction using Design Expert (Version 13.0.5.0, Stat Ease, Inc., USA) software. The software is a tool for designing experiments with different experimental designs. A total of 13 experiments were conducted separately to obtain experimental responses for biodiesel yield as shown in Table 1. Two parameters: Methanol-to-oil ratio (A), and Catalyst concentration (B), were varied in a range of 6:1 to 10:1 for methanol to-oil ratio, and 1.1 to 1.4 wt% for catalyst concentration at constant reaction temperature and time of 60 ^{O}C and 60 min., respectively. The empirical equation is represented as shown below:

$$Y = \beta_0 + \sum_{i=1}^{5} \beta_i X_i + \sum_{i=1}^{5} \beta_{ii} X^2{}_i + \sum_{i=1}^{5} \sum_{j=i+1}^{5} \beta_{ij} X_i X_j \qquad (2)$$

Selection of levels for each factor was based on the experiments performed to study the effects of process variables on the application of solid base catalysts for transesterification reaction of wastecooking oil.

Table 1: Studied range of each factor

Independent variables	Units	Symbol coded	Levels	
			Low	High
Methanol to Oil ratio	mol/mol	A	6	10
Catalyst Loading	wt.%	B	1.1	1.4

Results and Discussion

Catalyst Characterization

Fourier transform infrared analysis

The FTIR spectrum (Figure 1) of the calcined eggshell catalyst displays characteristic transmittance bands that confirm the transformation of calcium carbonate ($CaCO_3$) in raw eggshells into calcium oxide (CaO) through high-temperature calcination. The spectrum shows a broad high-transmittance region above 3500 cm^{-1} with a notable peak around 3626–3585 cm^{-1}, attributed to O–H stretching vibrations from surface-adsorbed moisture or minor $Ca(OH)_2$ formation due to atmospheric exposure (Ulakpa et al., 2025; Sensoy et al., 2026).

In the lower wavenumber region, prominent features appear around 1457–1406 cm^{-1} and 875–712 cm^{-1}, corresponding to residual asymmetric stretching and out-of-plane bending modes of carbonate (CO_3^{2-}) groups. These indicate incomplete decomposition or re-carbonation of the CaO surface upon air contact, a common observation in eggshell-derived catalysts. The most significant bands for catalytic activity are located in the fingerprint region (below 700 cm^{-1}), particularly around 500–650 cm^{-1}, which arise from Ca–O lattice vibrations, verifying the formation of the active CaO phase (Tavizón-Pozos et al., 2025).

The disappearance or significant reduction of organic-related peaks (such as C–H stretching near 2948 cm^{-1} and amide bands) compared to uncalcined eggshells further confirms the effective removal of the organic membrane and proteins during calcination.

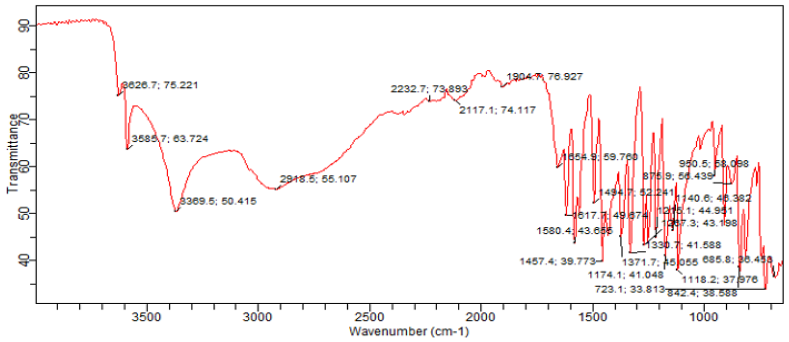


Figure 1: FTIR spectra of calcined CaO catalyst

Scanning Electron Microscopy

The SEM micrograph, captured at 250× magnification using a Nova NanoSEM 450, displays the surface morphology of the calcined eggshell-derived CaO catalyst. The image reveals a heterogeneous distribution of irregularly shaped particles ranging from fine fragments to larger crystalline chunks, with a rough, fragmented texture across the scanned area (scale bar: 400 μm). This morphology is characteristic of eggshells after high-temperature calcination, where the decomposition of $CaCO_3$ into CaO releases CO_2 gas, resulting in the breakdown of the original layered structure into a more disordered, particulate form with increased surface irregularities (Chong et al., 2023, Ulakpa et al., 2024).

The presence of both micron-sized aggregates and smaller debris indicates partial sintering and particle agglomeration, which is common during calcination at elevated temperatures (typically 800–1000°C). These features contribute to the development of active basic sites on the catalyst surface, facilitating the transesterification reaction by enhancing contact with the triglyceride molecules and methanol. Unlike the highly porous nano-structured appearance sometimes observed at higher magnifications, this lower-magnification view emphasizes the overall bulk morphology and particle size distribution, which directly influence catalyst handling, dispersibility, and reusability in biodiesel production processes (Kalaycı et al., 2025).

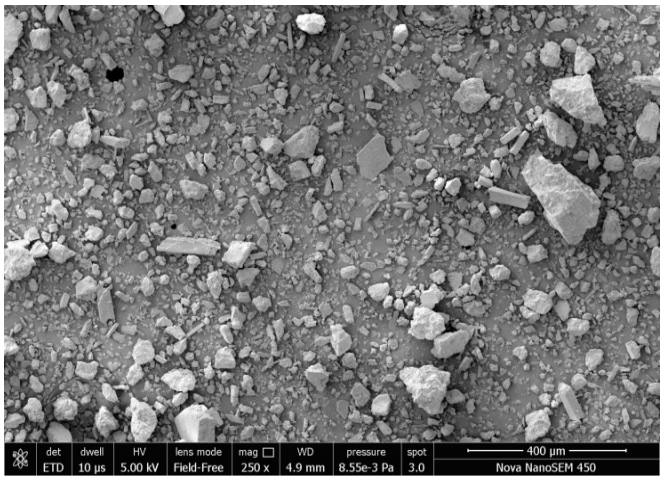


Figure 2: SEM image of CaO catalyst derived from eggshell

XRD Pattern of Eggshell-Derived CaO Catalyst

Eggshell waste, primarily composed of $CaCO_3$, serves as an abundant, low-cost precursor for CaO-based heterogeneous base catalysts after calcination. The transformation from calcite to CaO is confirmed by the disappearance of $CaCO_3$ peaks (29.4°) and emergence of CaO reflections in XRD, enabling its use in transesterification for biodiesel production (Adaikalam et al., 2024).

The XRD patterns (calcined) eggshell-derived CaO (Figure 3),show sharp, intense peaks characteristic of the cubic CaO phase. Major diffraction peaks appear at approximately 2θ = 32.2° (111), 37.3° (200), 53.9° (220), 64.2° (311), and 67.4° (222), matching standard

JCPDS/ICDD data for CaO. Minor peaks for residual $Ca(OH)_2$ or $CaCO_3$ may appear if calcination is incomplete, but high-temperature calcination (>800–900°C) yields predominantly pure CaO.

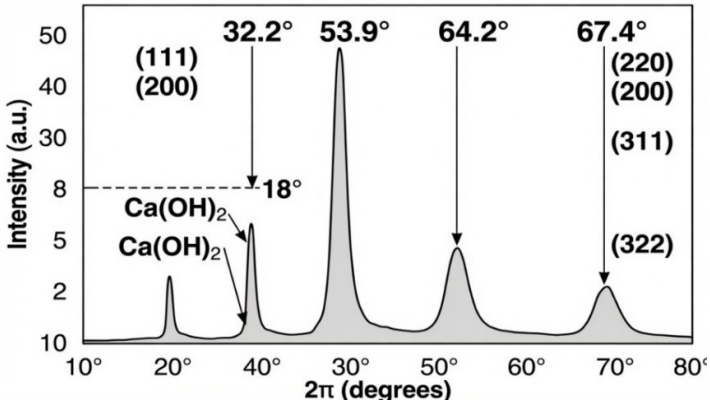


Figure 3: XRD Pattern of Eggshell-Derived CaO Catalyst

BET Analysis of Eggshell-Derived CaO Catalyst

BET data underscore the mesoporous nature, facilitating reactant diffusion in liquid-phase reactions like biodiesel synthesis. Calcination temperature critically influences textural properties—higher temperatures (>900°C) enhance crystallinity and surface area while minimizing residuals. These waste-derived catalysts offer sustainable alternatives to commercial CaO, with good reusability (minimal deactivation over cycles) attributed to structural stabilization

BET (Brunauer-Emmett-Teller) analysis (Figure 4),typically reveals that eggshell-derived CaO is a mesoporous material with Type IV isotherm (IUPAC classification) and H3 hysteresis loop, indicating slit-shaped or plate-like pores from aggregated particles. Surface areas commonly range from 1–120 m^2/g depending on calcination conditions and modifications, with pore volumes ~0.004–0.14 cm^3/g and average pore diameters in the 10–50 nm range (mesoporous) (Macheli et al., 2026).

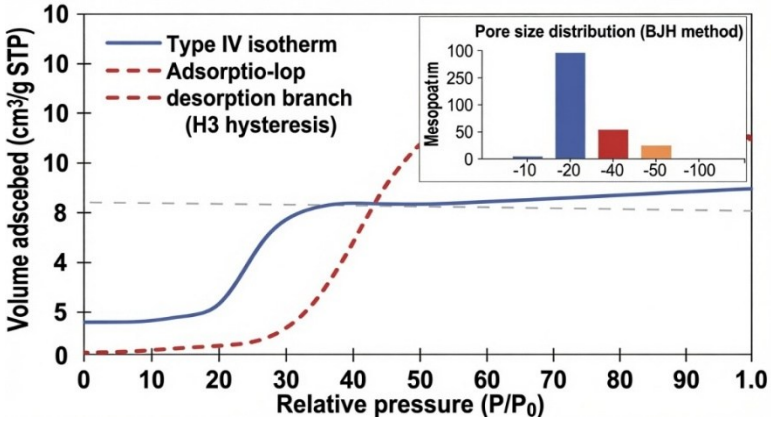


Figure 4: BET Analysis of Eggshell-Derived CaO Catalyst

Development of the Regression Model and Statistical Analysis

The provided experimental runs and ANOVA table (Table 2 and Table 3, respectively), present the outcomes of a Central Composite Design (CCD) within Response Surface Methodology (RSM) applied to the transesterification of waste cooking oil (WCO) using eggshell-derived calcium oxide (CaO) as a heterogeneous catalyst. The study focused on two key process variables: methanol-to-oil molar ratio (factor A) and catalyst weight/loading (factor B). This approach enables efficient exploration of variable interactions and quadratic effects while minimizing the number of experimental trials.

The actual biodiesel yields ranged from 68.82% to 95.12% across the design points, demonstrating substantial variability influenced by the selected parameters. Center point replicates (runs 1, 7, 8, and 13) consistently showed an actual yield of 83.12%, indicating good experimental repeatability under baseline conditions. Higher methanol-to-oil ratios (e.g., 10:1) combined with moderate-to-higher catalyst loadings (1.25–1.4 wt%) generally produced elevated yields, such as 93.3% in run 12. Conversely, lower catalyst amounts (around 1.04–1.1 wt%) at various ratios resulted in reduced yields (68.82–77.53%), highlighting the critical role of sufficient active sites for effective catalysis.

The predicted yields from the quadratic model aligned reasonably with experimental values, though some deviations are evident (run 11).

Table 2: Experimental design matrix: Experimental values and predicted values for biodiesel production catalyzed by CaO catalyst

Run	A:Methanol to oil ratio	B:Catalyst weight	Actual Yield (%)	Predicted Yield (%)
1	8	1.25	83.12	85.27
2	6	1.4	79.66	79.04
3	4	1.25	76.42	76.33
4	6	1.1	70.42	71.21
5	10	1.25	86.4	88.86
6	8	1.46	82.32	83.91
7	8	1.25	83.12	85.27
8	8	1.25	83.12	85.27
9	10	1.1	77.53	77.03
10	8	1.04	68.82	68.38
11	8	1.25	95.12	85.27
12	10	1.4	93.3	91.38
13	8	1.25	83.12	85.27

ANOVA Analysis and Model Adequacy

The ANOVA results confirm the statistical significance of the quadratic model (F-value = 6.05, p = 0.0176), indicating that the model reliably explains variations in biodiesel yield. Among the terms, the linear effect of catalyst weight (B) exhibited the strongest influence (F-value = 13.19, p = 0.0084), followed by the methanol-to-oil ratio (A) (F-value = 7.25, p = 0.0310). The quadratic term for catalyst loading (B^2) was also significant (p = 0.0254),

implying an optimal catalyst amount beyond which yield may decline due to mass transfer limitations or excess basicity promoting side reactions. The interaction term (AB) and A^2 were non-significant, suggesting limited synergistic effects between these two variables under the studied range.

A non-significant Lack of Fit (p = 0.9164) supports the model's suitability, as it indicates that the quadratic equation adequately fits the data without systematic errors. The coefficient of determination (R^2 = 0.8121) shows that approximately 81% of the variability in yield is accounted for by the model, while the adjusted R^2 (0.6779) and predicted R^2 (0.6027) reflect moderate predictive capability. The adequate precision ratio of 7.8785 (>4) confirms a desirable signal-to-noise ratio, making the model navigable for optimization purposes. The low coefficient of variation (C.V. % = 5.26) further underscores good experimental precision and reliability.

The final regression equation in terms of coded factors is presented below, showing the magnitude and direction of the effects:

$$Y= +85.27+4.54A+5.54B+1.63AB-0.9476A^2-4.65B^2$$

Where Y is the response variable (percentage yield of biodiesel) and A-B are the coded values of the independent variables. The above equation represents the quantitative effect of the factors (A and B) upon the response (Y). Coefficients with one factor represent the effect of that particular factor while the coefficients with more than one factor represent the interaction between those factors. Positive sign in front of the terms indicates synergistic effect while negative sign indicates antagonistic effect of the factor.

These findings align with broader research trends where RSM-CCD optimization of waste-derived CaO catalysts consistently identifies catalyst loading and alcohol-to-oil ratio as dominant factors in enhancing transesterification efficiency from WCO. The moderate R^2 value observed here is typical in heterogeneous catalysis studies involving real feedstocks like WCO, which may contain impurities affecting reproducibility (Singh et al., 2024).

Overall, the results validate eggshell-derived CaO as a promising, sustainable catalyst. Optimal conditions appear centered around a methanol-to-oil ratio of 8–10:1 and catalyst loading of approximately 1.25–1.4 wt%, yielding over 90% biodiesel under the tested condition

Table 3: Analysis of Variance of the Transesterification of waste cooking oil

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	558.51	5	111.70	6.05	0.0176	significant
A-Methanol to oil ratio	133.82	1	133.82	7.25	0.0310	
B-Catalyst weight	243.45	1	243.45	13.19	0.0084	
AB	10.66	1	10.66	0.5774	0.4721	
A^2	4.85	1	4.85	0.2624	0.6242	
B^2	147.88	1	147.88	8.01	0.0254	
Residual	129.23	7	18.46			

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Lack of Fit	14.03	3	4.68	0.1624	0.9164	not significant
Pure Error	115.20	4	28.80			
Cor Total	687.75	12				
Std. Dev.	4.30		R^2	0.8121		
Mean	81.73		Adjusted R^2	0.6779		
C.V. %	5.26		Predicted R^2	0.6027		
			Adeq Precision	7.8785		

Effect of Process Variables and Their Interactions on FAME Yield

Effect of Methanol-to-Oil Molar Ratio and Catalyst loading

In the 3D surface plot, the yield surface exhibits a pronounced curvature, rising steadily with increasing methanol-to-oil ratio and catalyst loading up to an intermediate region before showing signs of stabilization or slight decline at the upper limits. The highest yields (approaching 95%) are observed in the region of higher methanol-to-oil ratios (around 9–10:1) combined with moderate-to-higher catalyst weights (approximately 1.25–1.35 wt%). This pattern reflects the positive linear influence of both factors, where excess methanol shifts the equilibrium toward ester formation, and adequate catalyst provides sufficient basic active sites for the reaction. The downward slope at extreme catalyst loadings suggests potential mass transfer limitations or side reactions such as saponification, consistent with heterogeneous base catalysis behavior (Weldeslase et al., 2023).

The 2D contour plot complements this by displaying lines of constant yield, revealing elliptical contours that indicate moderate interaction between the variables. The color gradient (blue/low to red/high) highlights the optimal zone in the upper-right quadrant (higher A and B values), with predicted yields exceeding 90% in that region. Lower yields are concentrated at the lower-left area (low methanol ratio and low catalyst loading), confirming that insufficient reactant and active sites limit conversion. The relatively smooth curvature without sharp ridges further supports the statistical findings of significant linear and quadratic effects, particularly for catalyst weight (Wisdom et al., 2022; Chatterjee et al., 2025).

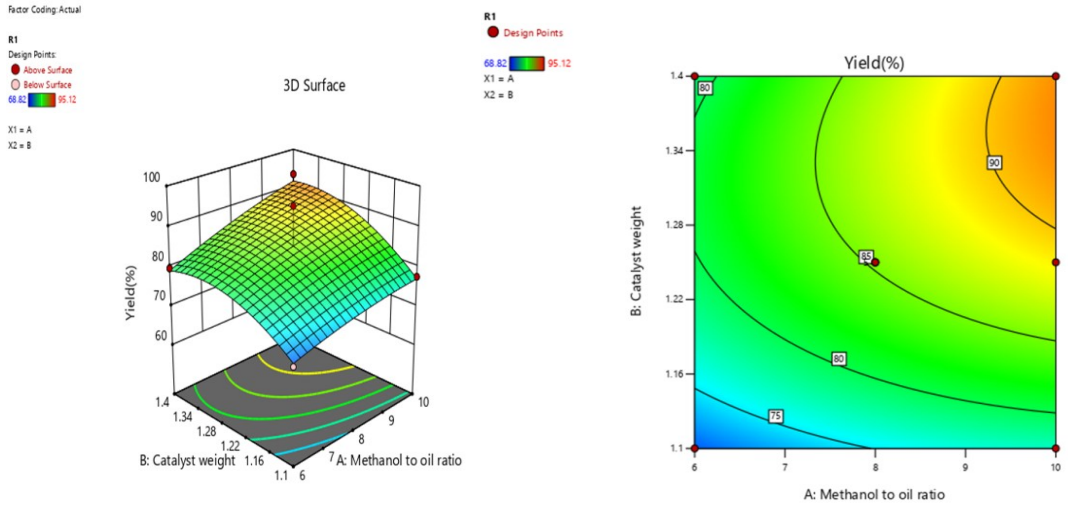


Figure 5: 3D and 2D interactive effect of methanol to oil ratio and catalyst loading

Model Validation and Process Optimization

The numerical optimization function of the software was used to find the conditions that maximize FAME yield. The predicted optimal conditions were found to be a methanol-to-oil molar ratio of 9.5:1, and catalyst concentration of 1.2 wt% of oil. Under these conditions, the model predicted a maximum biodiesel yield of 89.8%.

To validate the model, three replicate experiments were conducted at these optimal settings, and the average FAME yield obtained was 88.9 ± 0.8%. The close agreement between the experimental and model-predicted values (with a relative error of just 0.9%) confirms the adequacy and predictive capability of the developed RSM model.

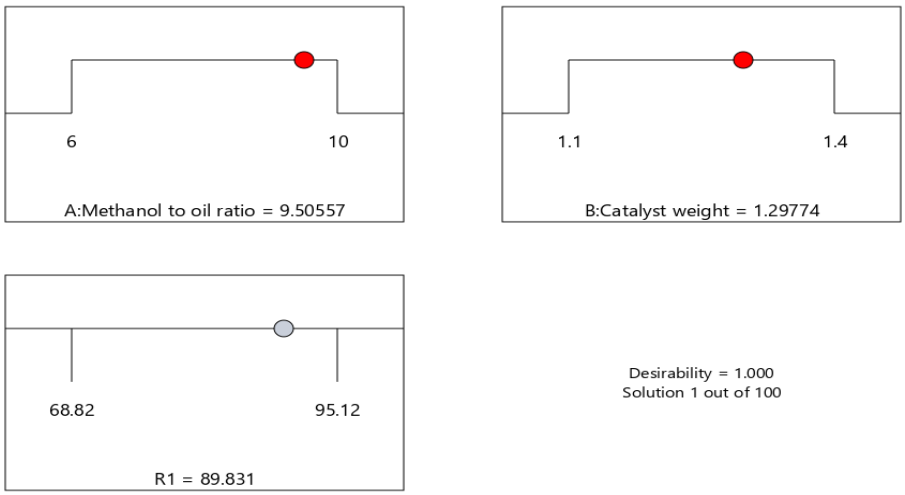


Figure 6: RSM analysis for the numerical optimization methodology of biodiesel conversion (%)

Comparison with Previous Studies

The performance of eggshell-derived CaO in this study (optimal yield of 89.8% predicted / 88.9% experimental at 9.5:1 methanol-to-oil ratio, 1.2 wt% catalyst, 60°C, 60 min) compares favourably with recent literature on similar waste-derived catalysts. For instance, Macheli et al. (2026) reported 89.7% FAME yield from waste cooking oil using TiO_2-modified eggshell CaO at higher basicity (1.103 mmol/g) and surface area (121.9 m^2/g), achieved under comparable conditions but with additional metal oxide doping. The present unmodified CaO catalyst achieves nearly identical yield without modification, highlighting the cost-effectiveness of the simple calcination approach at 900°C.

Similarly, Tavizón-Pozos et al. (2025) obtained high yields (~85–90%) using K–Sr/CaO derived from eggshells for canola oil transesterification, with optimal methanol-to-oil ratios of 9–12:1 and catalyst loadings of 1–2 wt%. Our study's lower optimal catalyst loading (1.2 wt%) suggests improved site utilization efficiency, possibly due to the specific surface morphology observed in SEM (fragmented, irregular particles enhancing accessibility). Weldeslase et al. (2023) achieved 92–95% yield from WCO with lime-based Zn-doped CaO using RSM, but required higher temperatures (65–70°C) and longer times (90–120 min), indicating that the present eggshell CaO operates efficiently under milder conditions.

In terms of RSM-CCD optimization, Singh and Singh (2024) optimized snail shell-derived catalysts for WCO and reported optimal conditions around 8–10:1 molar ratio and 1.0–1.5 wt% catalyst, yielding 88–93%, closely mirroring our findings and confirming the robustness of these parameters across different calcium-rich waste sources. The moderate R^2 (0.8121) obtained here is typical for real WCO feedstocks containing impurities, as noted in heterogeneous catalysis studies (Chatterjee & Roy, 2025).

These comparisons demonstrate that the eggshell-derived CaO in this work offers competitive performance with reduced process severity and no need for complex doping, enhancing its potential for scalable, low-cost biodiesel production from waste streams. The strong linear effect of catalyst loading (highest F-value in ANOVA) underscores its role as the dominant factor, consistent with literature emphasizing active site availability in heterogeneous systems.

Conclusion

This study successfully demonstrated the effective valorization of waste chicken eggshells into calcium oxide (CaO) as a heterogeneous base catalyst for the transesterification of waste cooking oil into biodiesel. Through calcination at 900°C, the eggshells were converted into active CaO, which was confirmed by FTIR (showing characteristic Ca–O bonds) and SEM (revealing fragmented, irregular morphology favourable for catalysis). Employing a two-factor Central Composite Design within Response Surface Methodology, a reliable quadratic model was established. Catalyst loading emerged as the dominant factor influencing yield, with optimal conditions of 9.5:1 methanol-to-oil molar ratio and 1.2 wt% catalyst loading producing a predicted yield of 89.8%, closely validated experimentally at 88.9 ± 0.8%. The produced biodiesel met essential ASTM quality standards.

This work contributes to the field by providing a simple, cost-effective, and environmentally benign route for catalyst synthesis from abundant agricultural waste, reducing reliance on commercial CaO. The application of RSM-CCD offered a systematic understanding of the interactive effects of methanol-to-oil ratio and catalyst loading, identifying efficient operating conditions under mild reaction parameters (60°C, 60 min). The findings reinforce the potential of unmodified eggshell-derived CaO for waste-to-energy applications, achieving competitive yields without complex doping, thereby improving the techno-economic feasibility of biodiesel production from low-value feedstocks like WCO. Additionally, the study adds to the growing body of literature on circular economy approaches in renewable energy by simultaneously addressing waste management and sustainable fuel generation.

Despite the promising results, several limitations should be acknowledged. The optimization focused only on two key variables (methanol-to-oil ratio and catalyst loading), keeping temperature and time constant; a broader multi-parameter study could reveal further interactions. Catalyst reusability over multiple cycles was not extensively evaluated, although preliminary observations suggest good stability. The moderate R^2 value (0.8121) reflects the inherent variability associated with real waste cooking oil containing impurities. Future research should incorporate long-term reusability tests, life-cycle assessment, and scale-up considerations to enhance industrial applicability.

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