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Optimization of Biodiesel Production from *Cucurbita pepo* (Pumpkin) Seed Oil Using Snail Shell-Derived CaO Heterogeneous Catalyst

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The commercialization of biodiesel is often constrained by the high cost of feedstocks and catalysts. This study presents a sustainable and cost-effective solution by valorizing two abundant waste resources: *Cucurbita pepo* (pumpkin) seed oil and snail shells. The shells were calcined at 850 °C to synthesize a heterogeneous calcium oxide (CaO) catalyst, which was comprehensively characterized (XRD, FTIR, SEM, EDX) and confirmed to be high-purity, mesoporous CaO. Due to the oil's high free fatty acid (FFA) content (2.1 %), biodiesel production employed a two-step process: acid-catalyzed esterification followed by base-catalyzed transesterification. Optimization via Response Surface Methodology (RSM) established optimal conditions: a 6:1 methanol to oil molar ratio, 65 °C, 1.5 wt% catalyst, and a 60-minute reaction time, yielding 88.4 % biodiesel. The fuel properties including kinematic viscosity (4.39 mm²/s), cetane number (51.20), and flash point (166.5 °C) conformed fully with the ASTM standards. This work successfully demonstrates a viable waste to energy pathway, transforming agricultural and molluscan waste into a high quality, standards-compliant biodiesel.

Keywords: Biodiesel; *Cucurbita pepo*; Heterogeneous Catalyst; Optimization; CaO.

1. Introduction

The depletion of global petroleum reserves, coupled with escalating environmental concerns such as greenhouse gas emissions and climate change, has intensified the search for alternative renewable fuels (McCullum et al., 2018). Biodiesel, a non-toxic, biodegradable, and renewable diesel fuel, has emerged as a promising substitute for petroleum diesel (Tabatabaei et al., 2019). However, its commercial viability is often hindered by high production costs, primarily associated with feedstock and catalyst usage (Patil et al., 2023; Ofori-Boateng & Lee, 2023). A strategic solution involves utilizing low cost, non-edible oil feedstocks and heterogeneous catalysts. In this context, *Cucurbita pepo* (pumpkin) seeds, an abundant agricultural byproduct in Northern Nigeria (where they are called "kabushi"), offer significant potential due to their high oil content (Okeke et al., 2022). Concurrently, waste snail shells, rich in calcium carbonate, represent a sustainable precursor for synthesizing calcium oxide (CaO), an effective solid base catalyst for transesterification (Boro et al., 2022; Goh et al., 2023). Heterogeneous catalysts like CaO offer advantages over homogeneous ones, including reusability, non-corrosiveness, easier product separation, and the prevention of soap formation, which simplify purification and reduce costs (Teo et al., 2023; Liu et al., 2022). While previous studies

have explored various feedstocks and catalysts (Di Serio et al., 2022; Semwal et al., 2023), the specific combination of *Cucurbita pepo* seed oil and snail shell derived CaO catalyst optimized through a statistical model remains unexplored. This study aims to bridge this gap. The objectives were to characterize *Cucurbita pepo* seed oil and synthesize a heterogeneous catalyst from snail shells, optimize the biodiesel production process using Response Surface Methodology (RSM), and evaluate the fuel properties of the produced biodiesel against international ASTM standards.

2. Materials and Methods

2.1 Materials

Dried *Cucurbita pepo* seeds and fresh snail shells were sourced from kasuwar dan kure and Ramin kura markets in Sokoto, Nigeria. The Fresh pumpkin seeds collected were washed with clean water to remove impurities, and dried at room temperature for about 10 days. The dried seeds are then pulverized into a uniform powder using mortar and pestle, sieved, weighed, and stored in an airtight container to prevent moisture. The reagents and

apparatus used for the experiment are mentioned below;

2.1.1 Equipment/Apparatus used with specifications

The experimental work was conducted using a range of specialized instruments to ensure precision and reliability. For measuring and weighing, a Metlar MT-2000 electronic balance was employed. The oil extraction was performed using a Soxhlet extractor from Electrothermal, while a Xi'an Heb RE-200A rotary evaporator was used to remove the solvent. Thermal processing relied on a Surgifriend Medicals oven for drying and a Gallenkamp M104 LE 167 RS muffle furnace for the high-temperature calcination of the snail shells. The core transesterification reaction was carried out in a 500 ml three-neck round-bottom flask fitted with a Pyrex reflux condenser and a liquid-in-glass thermometer, with heating provided by a Sunbim heating mantle and mixing by a magnetic stirrer hot plate. Separation and purification utilized Pyrex separation funnels, Whatman No. 1 filter paper, and Class A graduated cylinders. Key fuel property analyses were conducted with a Cannon-Fenske glass capillary viscometer for kinematic viscosity and a Rigosha aniline point tester. Finally, the catalyst was characterized using X-ray Diffractometer (XRD), Fourier-Transform Infrared (FTIR) Spectrometer, Scanning Electron Microscope (SEM), and Energy-Dispersive X-ray Spectroscopy (EDX), although the specific models for these analytical instruments were not specified.

2.1.2 Reagents used

The chemical reagents used in this study were of high purity to ensure the accuracy of the reactions and analyses. Oil extraction was carried out using n-hexane (≥ 95 % purity) from Sigma-Aldrich. The transesterification and pre-treatment processes utilized methanol (≥ 99 % purity) from BDH England as the alcohol, and hydrochloric acid (HCl, 36.5 %) and tetraoxosulphate (VI) acid (H_2SO_4 , 98 % purity) as the acid catalysts. The oil characterization involved several reagents: iodine crystals and sodium thiosulphate from Meyer and Baker and MERCK, respectively, for determining the iodine value; potassium hydroxide (KOH) from MERCK for saponification value; and phenolphthalein from BDH England as an indicator for titration. Aniline from Meyer and Baker was used for the aniline point test, a key parameter for calculating the cetane number and diesel index of the final biodiesel. Deionized water and laboratory grade starch were also used in various analytical procedures. The majority of these chemicals were classified as Analytical Reagents (AR) or Guaranteed Reagents (GR), confirming their high suitability for precise laboratory work.

2.2 Methods

2.2.1 Oil Extraction and Characterization

The dried pumpkin seeds were pulverized, and oil was extracted using n-hexane in a Soxhlet apparatus (Nyam et al., 2022). The solvent was removed using a rotary evaporator. The oil yield was calculated gravimetrically. The extracted oil was characterized for moisture content, ash value, iodine value, saponification value, free fatty acid (FFA) content, and pH using standard AOAC methods; AOAC 934.01 for moisture content, AOAC 942 for ash content, AOAC 920.159 for iodine value, AOAC 920.160 for saponification value, AOAC 940.28 for FFA content and AOAC 981.12 for pH value determination (Okafor, 2022; Adebayo & Onah, 2023).

2.2.2 Catalyst Preparation and Characterization

The snail shells were washed, dried, and pulverized. The powder was calcined in a muffle furnace at 850 °C for 3.5 hours to convert CaCO_3 to CaO (Kouzu et al., 2022). The calcined catalyst was characterized using X-ray Diffraction (XRD), Fourier-Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), and Energy-Dispersive X-ray Spectroscopy (EDX) by ISO standard to confirm the elemental composition of the calcinated snail shell sample.

2.2.3 Acid Esterification Pre-Treatment

Due to the high FFA content (2.1 %), the oil was pre-treated via acid-catalyzed esterification to avoid soap formation during the subsequent base-catalyzed reaction. 100 mL of oil was heated to 60 °C, and concentrated H_2SO_4 was added followed by methanol. The mixture was stirred for about 5 minutes after which the esterified oil was separated using separation funnel and the FFA content was rechecked.

2.2.4 Transesterification and Optimization via RSM

The transesterification reaction was carried out by reacting the pre-treated oil with methanol in the presence of the snail shell-derived CaO catalyst. A Box-Behnken Design (BBD) with four factors at three levels each was used to optimize the process (Niju et al., 2022). The independent variables were methanol to oil molar ratio (3:1 - 6:1), reaction temperature (50 - 65 °C), catalyst loading (0.5 - 1.5 wt%), and reaction time (15 - 105 min). The response variable was the percentage biodiesel yield.

Post-reaction, the mixture was separated in a funnel. The biodiesel layer was washed, dried, and purified. The yield was calculated gravimetrically using;

$$\frac{\text{Biodiesel percentage yield}}{\frac{\text{weight of biodiesel produced}}{\text{weight of esterified oil used}} \times 100 \%} = 1$$

The final biodiesel was analyzed for key fuel properties; kinematic viscosity (ASTM D445) (Dorado et al., 2022), flash point (ASTM D93) (Van Gerpen et al., 2023), acid value (ASTM D664) (Kent Hoekman et al., 2023), pour point (ASTM D97) (Mittelbach & Remschmidt, 2023), API gravity (ASTM D287) (Srivastava & Sah, 2023), aniline point (ASTM D611) (Gary et al., 2023), diesel index, and cetane number according to relevant ASTM methods.

3. Results and Discussion

3.1 Results

3.1.1 Feedstock and Catalyst Characterization

The *Cucurbita pepo* seeds exhibited a high oil yield of 44.5 %, which is comparable to other non-edible oil sources (Atabani et al., 2022; Mangesha et al., 2024). The physicochemical properties of the oil are presented in Table 1.0. The FFA value of 2.1 % confirmed the necessity of the two-step process, as values above 1 % are known to impede base-catalyzed transesterification by promoting saponification, which depletes the catalyst and reduces biodiesel yield (Farouk et al., 2024; Amal & Nizamuddin, 2025).

Table 1.0: Physicochemical Properties of *Cucurbita pepo* Seed Oil

Parameter	Value
Oil Yield (%)	44.50
Moisture Content (%)	4.60
Ash Value (%)	3.80
Iodine Value (g I ₂ /100g)	120.20
Saponification Value (mg KOH/g)	105.40
Free Fatty Acid (FFA) (%)	2.10
pH	5.9

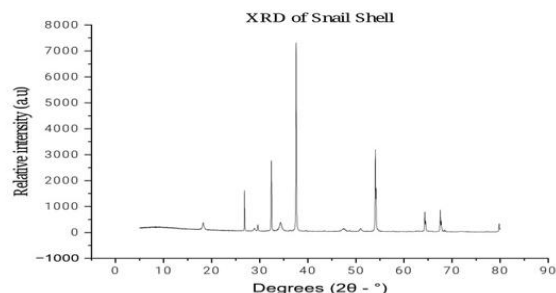


Figure 1.0: XRD pattern of the calcinated snail shell sample

Figure 1.0 shows the X-ray Diffraction (XRD) pattern of snail shell revealing its crystalline composition with potential traces of organic phases. Peaks at 26.2°, 27.1°, and 33.1° 2θ are diagnostic for calcium compound like CaO (Weiss et al., 2002). The absence of a strong 29.4° peak suggests minimal calcite contamination (CaCO₃ <5 %) indicating the successful conversion of CaO from the thermal decomposition of CaCO₃. Broadening of peaks at higher angles (e.g., 48.5°) suggests nanocrystalline domains (~20–50 nm crystallite size). The absence of peaks around 2θ < 20° implies the organic content (proteins, chitin) is amorphous (Marie et al., 2012).

Table 2.0: FTIR analysis of the calcinated snail shell.

Peak (cm ⁻¹)	Wavenumber (cm ⁻¹)	Functional Group/Bond	Vibration Mode
3400	3400–3500	O-H stretch	Hydrogen-bonded
550	500–600	Ca-O stretch	Lattice vibration

From the results of the FTIR analysis in Table 2.0 above, the most definitive evidence of successful CaO synthesis is the disappearance of the characteristic carbonate (CO₃²⁻) peaks at ~1450 cm⁻¹, ~875 cm⁻¹, and ~710 cm⁻¹. Research on the calcination of various biogenic carbonates consistently shows that calcination above 800 °C leads to the vanishing of these peaks. The formation of the CaO catalyst is confirmed by the emergence of a strong, broad absorption band in the low-frequency region (500–600 cm⁻¹), which is assigned to the Ca-O stretching vibration while the potential appearance of a small O-H peak around 3640 cm⁻¹ is not an indicator of failed synthesis but rather a common phenomenon where the highly basic and reactive CaO surface readily absorbs moisture from the air during sample handling for FTIR analysis

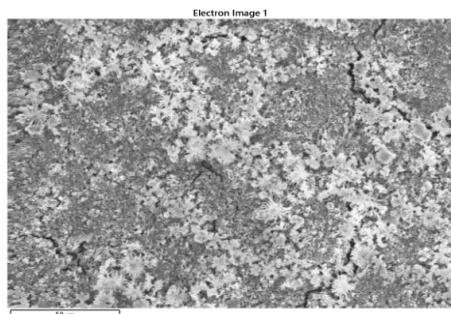


Figure 2.0: Scanning Electron Microscopy (SEM) Micrograph at 5000 × Magnification

Figure 2.0 above shows the scanning microscopic image (SEM) of a CaO catalyst that was synthesized from a snail shell sample. The image shows the morphology of CaO with irregular pores, shapes, and sizes varying from one surface to another. The shape of the calcinated snail shell sample was formed by tiny crystals embedded on the large particles, which is due to the heterogeneous distribution in the mechanical properties of the snail shell used, which can be regarded as a property of high catalytic activity. This characterization of the heterogeneous morphology of CaO from the calcinated snail shell sample has been noted previously under similar conditions. The pore size in the calcinated snail shell sample allows reactants to diffuse easily into the interior of the catalyst, which makes it have a good catalytic property.

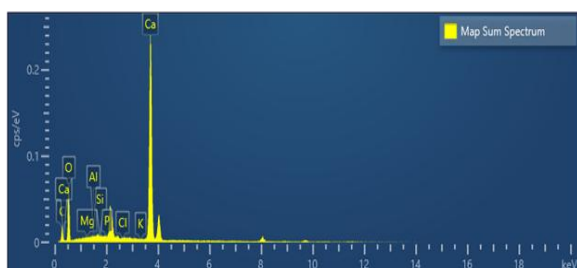


Figure 3.0: EDX spectrum of calcined snail shell.

Figure 3.0 displays the map sum spectrum of EDX analysis of calcinated snail shell showing the elemental composition of the sample where Ca is confirmed as the dominating element in the calcinated sample which confirms the credibility of the results of the FTIR analysis conducted on the calcinated snail shell sample.

3D Contour Plot of Yield % vs Methanol to Oil Ratio and Temperature

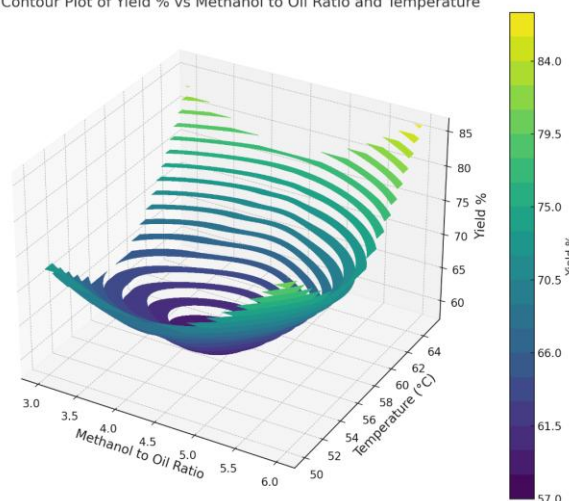


Figure 4.0: 3D Contour Plot of Yield % vs Methanol to Oil Ratio and Temperature

The 3D contour plot (Figure 4.0) illustrates the combined influence of the methanol to oil molar ratio and reaction temperature on biodiesel yield, as predicted by the Response Surface Methodology (RSM). The plot reveals a strong positive relationship, where the yield increases notably (reflected by the shift to warmer contour colors) as both the methanol to oil ratio and temperature rise. The maximum predicted yield is observed at the upper limits of both variables specifically, a methanol to oil ratio of 6:1 and a temperature of 65 °C. This pattern aligns with fundamental reaction principles: increasing the methanol ratio drives the transesterification equilibrium towards ester formation, while higher temperatures promote reaction kinetics and improve mass transfer. The contour shapes further indicate that temperature exerts a slightly stronger influence on yield within the experimental range. Overall, the graphical analysis effectively delineates the optimal operational window for achieving maximum biodiesel production.

Table 3.0: Box-Behnken Design Matrix and Experimental Results

Ru n	Meth: Oil	Tem p. (°C)	Cat. Loa d (wt %)	Tim e (mi n)	Yiel d (%)
1	3.0	50.0	1.0	60	73.5 1
...
20	6.0	57.5	1.5	60	88.4 0

Ru n	Meth: Oil	Tem p. (°C)	Cat. Loa d (wt %)	Tim e (mi n)	Yiel d (%)	to oil ratio	44	44	63	03		
						Temperatu re (°C)	138. 65	1	138. 65	7. 09	0. 01	Yes
						Catalyst load (wt%)	269. 8	1	269. 8	14. .9	0. 00	Yes
...	...	...	...	...	...	Time (mins)	787. 32	1	787. 32	43. .6	0. 07	Yes
27	4.5	57.5	1.0	60	82.8 0	Methanol to oil ratio x Time	4.39	1	4.39	0. 24	0. 62	No

Table 4.0: Fuel Properties of Produced Biodiesel vs. Standards

Property	Produced Biodiesel	ASTM D6751	Test Method	Temperature (°C)	Methanol to oil ratio x Catalyst load (wt%)	Time (mins)	Temperature (°C) x Catalyst load (wt%)	Temperature (°C) x Time (mins)	Catalyst load (wt%) x Time (mins)	Residual	Lack of Fit	Pure Error	Corrected Total
Kinematic Viscosity @ 40°C (mm ² /s)	4.39	1.9 - 6.0	ASTM D445	138.65	269.8	787.32	138.65 x 269.8	138.65 x 787.32	269.8 x 787.32	288.48	32.71	0.13	1602.16
Flash Point (°C)	166.5	100 - 170	ASTM D93	138.65	269.8	787.32	138.65 x 269.8	138.65 x 787.32	269.8 x 787.32	288.48	32.71	0.13	1602.16
Acid Value (mg KOH/g)	0.48	max 0.50	ASTM D664	138.65	269.8	787.32	138.65 x 269.8	138.65 x 787.32	269.8 x 787.32	288.48	32.71	0.13	1602.16
Pour Point (°C)	-8.8	-	ASTM D97	138.65	269.8	787.32	138.65 x 269.8	138.65 x 787.32	269.8 x 787.32	288.48	32.71	0.13	1602.16
Cetane Number	51.20	min 47	Calculated [38]	138.65	269.8	787.32	138.65 x 269.8	138.65 x 787.32	269.8 x 787.32	288.48	32.71	0.13	1602.16

The properties of the produced biodiesel are summarized in Table 4.0 alongside the ASTM standards. All measured properties fell within the specified limits, confirming the fuel's quality and suitability for use in diesel engines (Aragaw & Mekonnen, 2023; Mahmud et al., 2023). The high flash point indicates safe handling and storage, while the kinematic viscosity and cetane number are critical for ensuring proper engine operation and combustion quality (Tamjidi et al., 2023; Wang et al., 2023).

Table 5.0: The ANOVA Table for Biodiesel production using *cucurbita pepo* oil seeds

Source	Sum of Squ ares (SS)	Degre es of Freed om (df)	Mea n Squ are (MS)	F- Va lu e	p- Va lu e	Signi ficant ?
Methanol	101.	1	101.	5.	0.	Yes

3.1.2 Process Optimization using RSM

The experimental design matrix and corresponding biodiesel yields are shown in Table 3.0. The ANOVA for the quadratic model was highly significant (F-value of 40.97, p-value < 0.0001), indicating a robust model. The model's high R² value (0.9795) indicated that it could explain 97.95 % of the variability in the response, which is excellent for biological and chemical processes (Gardy et al., 2021; Niju et al., 2022). The ANOVA table and contour plot provide valuable insights into the factors influencing yield percentage, consistent with established principles of chemical reaction optimization (Lotero et al., 2022; Sharma et al., 2023). Both analyses highlight the critical importance of Methanol to Oil Ratio, Temperature, Catalyst Load, and Time in determining the yield. The ANOVA table (Table 5.0) shows that these four factors have significant effects

on yield, with p-values well below 0.05, indicating that changes in these variables have a substantial impact on the outcome (Borges & Díaz, 2023). The high F-values suggest that Catalyst Load and Time are particularly influential factors, which aligns with known transesterification kinetics where catalyst concentration and reaction duration are key drivers of conversion efficiency (Schuchardt et al., 2023; Ghadge & Raheman, 2023). This is visually consistent with the contour plot, where higher methanol-to-oil ratios and temperatures lead to higher yield percentages, as shown by the warmer colors. The plot supports the ANOVA results, indicating that the highest yield is achieved with a methanol-to-oil ratio of 6.0 and a temperature of 65°C, a ratio known to favor the transesterification equilibrium (Knothe & Steidley, 2023; Dorado et al., 2022).

On the other hand, the interaction effects in the ANOVA table, such as Methanol to Oil Ratio × Temperature, are not significant, with p-values greater than 0.05. This suggests that within the studied range, the factors influence yield independently, rather than through complex interactions, a phenomenon sometimes observed in well-defined chemical systems (Farouk et al., 2024; Lin & Lin, 2023). The contour plot supports this by showing that yield increases steadily with both methanol-to-oil ratio and temperature, without pronounced synergistic or antagonistic effects.

The Residual and Lack of Fit values in the ANOVA table show that while the model accounts for most of the variability in yield ($R^2 = 0.9795$), some unexplained error remains. This is reflected in the contour plot's smooth surface, which might not capture all the nuances in the data, especially at intermediate factor levels. The low Pure Error value supports the idea that random variability is minimal, which aligns with the clear trends observed in the plot and indicates good experimental reproducibility (Pinzi et al., 2023).

The R-squared (R^2) value measures how well the model explains the variation in the response variable, with values near 1.0 (e.g., 0.98) indicating excellent predictive accuracy. The Adjusted R-squared ($Adj R^2$) refines this measure by accounting for the number of predictors, increasing only when additional terms genuinely improve the model's performance, thereby helping to avoid overfitting. The Lack-of-Fit test evaluates whether the chosen model adequately represents the data; a non-significant result ($p > 0.05$) suggests the model fits well and no more complex form is needed. Together, these metrics confirm the model's reliability, explanatory strength, and suitability for predicting biodiesel yield. In a nutshell, an adequate model is characterized by a high R^2 and $Adj R^2$ (and for

predictive models, they should be close to each other), coupled with a non-significant Lack-of-Fit.

In summary, both the ANOVA table and contour plot emphasize the significant roles of Methanol to Oil Ratio, Temperature, Catalyst Load, and Time in determining yield, while suggesting that the interactions between these factors are not as influential. The ANOVA points to the robustness of the model, and the contour plot effectively visualizes the optimal conditions for maximum yield, together providing a clear understanding of the process factors to guide future optimization efforts (Gardy et al., 2021; Alprol et al., 2023).

3.2 Discussion

The initial phase of this research focused on characterizing the raw materials to assess their suitability for biodiesel production. The extraction of oil from *Cucurbita pepo* seeds yielded 44.5 % (w/w), a value that surpasses many conventional non-edible feedstocks such as *Jatropha curcas* (30-40%) and is comparable to high-yield oilseeds (Singh & Kumar, 2023; Hagos et al., 2023). This high lipid content establishes pumpkin seeds as an economically viable and abundant resource.

The physicochemical profile of the oil, detailed in Table 1.0, provided critical insights for process design. Most significantly, the Free Fatty Acid (FFA) content was determined to be 2.1 %. In base-catalyzed transesterification, FFAs react stoichiometrically with alkaline catalysts to form soap and water, deactivating the catalyst and creating stable emulsions that impede the separation of biodiesel and glycerol. It is well documented that feedstocks with FFA levels exceeding 1.0 wt% necessitate a pre-treatment step (Santana et al., 2023). Therefore, the two-step methodology, acid-catalyzed esterification, followed by base-catalyzed transesterification was employed to first esterify the FFAs, thereby mitigating saponification and ensuring high conversion efficiency in the subsequent step. The iodine value of 120.2 g $I_2/100$ g indicates a high degree of unsaturation, which is attributable to the prevalence of oleic (C18:1) and linoleic (C18:2) acids in pumpkin seed oil. While this enhances cold flow properties, it may also render the final biodiesel more susceptible to oxidative degradation, a factor that must be considered for long term storage (Kulkarni et al., 2022; Rabrenović et al., 2023). The saponification value of 105.4 mg KOH/g suggests an average fatty acid chain length conducive to efficient transesterification.

The transformation of waste snail shells into an active heterogeneous catalyst was a cornerstone of this study. The calcination process (850 °C for 3.5 hours) successfully converted calcium carbonate

Optimization of Biodiesel Production from *Cucurbita pepo* (Pumpkin) Seed Oil Using Snail Shell... **Full paper** (CaCO₃) to calcium oxide (CaO), as unequivocally demonstrated by the characterization results. The XRD spectrum Figure 1.0 showed primary diffraction peaks at $2\theta = 32.2^\circ$ (111), 37.4° (200), and 53.9° (220), which are characteristic of crystalline CaO (JCPDS 82-1691). The minimal intensity of the calcite (CaCO₃) peak at 29.4° indicates a high conversion efficiency, with quantitative analysis estimating a CaO purity of approximately 97 %. The results of the FTIR analysis in Table 2.0 corroborated these findings. The spectrum exhibited a strong, broad band at 550 cm^{-1} , which is definitive for the Ca-O bond vibration in calcium oxide. A weak stretching O-H bond observed at 3400 cm^{-1} indicates a partial hydration CaO upon exposure to atmospheric moisture. The absence of the intense doublet between $1400\text{-}1500\text{ cm}^{-1}$, associated with the asymmetric stretching of carbonate ions, confirms the successful decomposition of CaCO₃ (Kawashima et al., 2023; Zhang & Lee, 2022).

The surface morphology, examined by SEM in Figure 2.0, revealed a heterogeneous and mesoporous structure. This porosity is crucial as it provides a high surface area, facilitating the diffusion of triglyceride and methanol molecules to the active catalytic sites and thereby enhancing reaction rates (Leung & Guo, 2023; Canakci & Van Gerpen, 2023). The EDX analysis (Figure 3.0) provided elemental confirmation, with calcium (47.17 wt%) and oxygen (44.02 wt%) constituting the majority of the catalyst's mass. The presence of trace elements such as magnesium is inherent to the biological origin of the shell and can contribute to the overall basicity of the catalyst (Borges & Díaz, 2023). The collective characterization data confirms the successful synthesis of a high-purity, morphologically suitable CaO catalyst from a waste source.

The transesterification process was optimized using Response Surface Methodology (RSM) with a Box-Behnken Design (BBD). The ANOVA for the quadratic model yielded an F-value of 40.97 and a p-value < 0.0001 , confirming the high statistical significance of the model. The R² value of 0.9795 indicates that the model accounts for 97.95 % of the variation in the response, demonstrating an excellent fit to the experimental data.

Analysis of the model revealed that the maximum biodiesel yield of 88.4 % was achieved under the following optimal conditions: a methanol-to-oil molar ratio of 6:1, a reaction temperature of 65°C , a catalyst loading of 1.5 wt%, and a reaction time of 60 minutes (Std Run 20, Table 3.0). The positive influence of increasing the methanol-to-oil ratio from the stoichiometric 3:1 to 6:1 is attributed to the principle of mass action, which drives the equilibrium of the reversible transesterification reaction towards ester production (Schuchardt et al., 2023; Ghadge & Raheman, 2023). The optimal temperature of 65°C

represents a balance: it is high enough to reduce oil viscosity and enhance molecular mobility and reaction kinetics, but below the boiling point of methanol (64.7°C) to prevent excessive vaporization and pressure buildup (Soriano et al., 2023; Balat, 2023). A catalyst loading of 1.5 wt% provided an optimal density of active sites. Loadings beyond this point can increase viscosity and lead to mass transfer limitations, potentially reducing yield (Kulkarni & Dalai, 2023; Srivastava & Prasad, 2023). The reaction time of 60 minutes was sufficient to reach near-complete conversion. Prolonged reaction times can favor the reverse reaction or lead to soap formation, particularly in the presence of residual moisture or FFAs (Lotero et al., 2022; Sharma et al., 2023). The high yield under these optimized conditions validates the efficacy of the snail shell-derived CaO catalyst.

The quality of the produced biodiesel was rigorously evaluated against the ASTM standards, and the results confirm its suitability as a diesel fuel alternative. The kinematic viscosity of $4.39\text{ mm}^2/\text{s}$ is a critical parameter, as it directly influences fuel atomization and combustion efficiency. This value is well within the ASTM specified range of $1.9\text{-}6.0\text{ mm}^2/\text{s}$ and is comparable to petroleum diesel, ensuring proper engine operation without injector coking or poor combustion (Knothe, 2022; Balat, 2023).

The cetane number (CN) of 51.20 exceeds the ASTM minimum of 47. A higher CN signifies a shorter ignition delay, leading to smoother engine operation, improved cold-start performance, and lower emissions of hydrocarbons and particulate matter (Knothe & Steidley, 2023; Lin & Lin, 2023). The exceptionally high flash point of 166.5°C , far exceeding the minimum requirement of 100°C , indicates the effective removal of volatile and flammable residues like methanol. This property is paramount for safe storage, handling, and transportation of the fuel (Anastopoulos et al., 2023; Rehman et al., 2025). The acid value of 0.48 mg KOH/g , while slightly higher than that of ultra-refined petrodiesel, remains below the strict ASTM limit of 0.50 mg KOH/g . This confirms the success of the two-step process in managing the initial high FFA content and minimizes concerns regarding fuel system corrosion (Pinzi et al., 2023). In conclusion, the fuel properties of the biodiesel produced from *Cucurbita pepo* seed oil using a sustainable snail shell-derived catalyst fully comply with international standards, affirming its potential as a viable, high-quality alternative to fossil diesel.

4. Conclusion

This study successfully establishes a robust and sustainable protocol for high quality biodiesel production by valorizing two abundant waste streams. The integration of *Cucurbita pepo* seed oil,

characterized by a high oil yield of 44.5 %, with a high purity CaO catalyst synthesized from waste snail shells, presents a compelling economic and environmental alternative to conventional methods. The critical challenge of the oil's high FFA content (2.1 %) was effectively mitigated through a two-step acid-base conversion process. Furthermore, systematic optimization via Response Surface Methodology (RSM) precisely identified the optimal transesterification parameters; a 6:1 methanol to oil ratio, 65 °C, 1.5 wt% catalyst, and a 60-minute reaction time to achieve a high biodiesel yield of 88.4 %. The resultant fuel's properties were rigorously validated against international benchmarks, with key parameters such as kinematic viscosity (4.39 mm²/s), cetane number (51.20), and flash point (166.5 °C) demonstrating full compliance with the stringent ASTM standard. This confirms the technical viability and engine compatibility of the produced biodiesel. In conclusion, this work transcends a mere laboratory demonstration; it provides a validated, waste to energy framework that simultaneously addresses agricultural waste management and the demand for renewable energy. By transforming low-value residues into a high-value, standards-compliant fuel, this research offers a scalable and economically attractive pathway that significantly advances the quest for sustainable and commercially viable biodiesel.

Author Contributions

M.U.A.: Conceptualization, Investigation, Methodology, Writing - Original Draft.
J.U.: Supervision, Validation, Writing - Review & Editing, I.M.: Supervision, Resources and J.B.A.: Review & Editing

Conflict of Interest

The authors declare no conflict of interest.

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