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Acid-Catalyzed Synthesis of Biodiesel from Calabash (*Crescentia cujete*) Seed Oil

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Abstract: This study evaluated the acid-catalyzed production of biodiesel from Calabash (*Crescentia cujete*) seed oil using sulfuric and nitric acids as transesterification catalysts. Oil extracted by Soxhlet extraction yielded 35.20% and was converted into biodiesel under various reaction conditions to determine the optimum catalyst loading, reaction time, temperature, and oil-to-methanol molar ratio. Sulfuric acid exhibited superior catalytic performance, achieving the highest biodiesel yield of 91.20% at 4% catalyst loading, 65 °C, 4 h, and an oil-to-methanol molar ratio of 1:12. Under optimum conditions, nitric acid produced a lower yield of 65.85% at 3% catalyst loading, 65 °C, 6 h, and a molar ratio of 1:9. GC-MS analysis identified seven methyl esters in the sulfuric acid-derived biodiesel, predominantly methyl hexadecanoate (16.93%), methyl stearate (15.07%), and methyl 9-octadecenoate (43.64%). Biodiesel synthesized using nitric acid contained eight methyl esters, with methyl hexadecanoate (16.55%), methyl stearate (26.90%), and methyl 9-hexadecenoate (21.51%) as the major components. The corresponding burning rates were 1.96×10^{-3} and 2.71×10^{-3} cm²/s for sulfuric and nitric acid catalysts, respectively. Overall, sulfuric acid proved more effective, producing higher biodiesel yield in a shorter reaction time and demonstrating the potential of *C. cujete* seed oil as a non-edible biodiesel feedstock.

Keywords: Acid-catalyzed; Biodiesel; *Crescentia cujete*; Optimization; Transesterification

Introduction

Energy demand in Indonesia has been increasing from year to year. This rise in energy consumption is not only due to the expansion of the industrial sector, but also the rapidly growing needs of land, sea, and air transportation. Meanwhile, fossil fuel reserves are depleting, and oil prices continue to rise annually (Ang et al., 2022; Suripto & Japa, 2024). Given the increasing energy crisis and the uncontrolled rise in fuel demand, it is necessary to develop the potential of plants as alternative sources of fuel. One of the promising renewable sources is vegetable oil. Vegetable oils can be obtained from canola seeds, sunflower seeds, rubber seeds, used cooking oil, and others (Manurung et al., 2025; Munir et al., 2020; Sangar et al., 2019).

In the Maluku region, several plants can produce vegetable oil, one of which is the Calabash fruit. Calabash is commonly known as an ornamental plant and is not consumed by the local community. The outer shell is often used to make household utensils such as water dippers, spice containers, flowerpots, and others, while the inner part is usually discarded as waste. However, the inner part of the Calabash fruit contains significant amounts of fat and energy and thus has potential as an alternative energy source (Gaspers et al., 2024).

Biodiesel is a liquid fuel that contains ester compounds and is derived from plant-based oils, suitable for use in diesel engines and other vehicles such as planes and cars. Biodiesel is a renewable, environmentally friendly, non-toxic, sulfur-free fuel that emits less smoke, is biodegradable, and helps reduce harmful emissions (CO_2, SO_2) compared to petroleum-based diesel (Cerón Ferrusca et al., 2023).

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The production of biodiesel generally involves a chemical process called transesterification, where triglycerides (from oil) react with alcohol to form esters (biodiesel) and glycerol. The primary raw materials used in biodiesel production include vegetable oil, animal fat, or waste oil. Alcohols typically used in the transesterification of vegetable oils include methanol, although ethanol, isopropanol, and butanol can also be used. However, the water content in alcohol must be considered, as high moisture levels can affect the quality of the resulting biodiesel (Verma et al., 2016).

Catalysts are essential in biodiesel production to improve solubility and reaction efficiency. Commonly used catalysts include homogeneous catalysts such as acids and bases (Kim et al., 2025; Ramdhani et al., 2023; Su & Guo, 2014). Typical acid catalysts are HNO_3, H_2SO_4, and HCl, while base catalysts include NaOH, KOH, and sodium methoxide (Samad et al., 2018). Biodiesel produced via transesterification of vegetable oils or animal fats using either acid or base catalysts generally consists of hydrocarbon chains containing 16–20 carbon atoms (Adeyemi et al., 2023; Ejeheri et al., 2025; Ibrahim et al., 2016; Torres et al., 2017).

Research by Rahim and Prihatiningtyas (2015) showed that biodiesel synthesized from rubber seeds using H_2SO_4 catalyst achieved a yield of 55%, with ethyl ester content of 13.43%. Smith (1947) reported that Calabash seed oil contains 19.7% saturated fatty acids, 59.4% oleic acid, 19.3% linoleic acid, and 1.6% linolenic acid. Furthermore, Yen et al. (2022) found that Calabash seed oil has an oil content of 16.44% and contains seven fatty acids, including palmitic acid (19.56%), stearic acid (3.85%), nonadecanoic acid (1.20%), eicosanoic acid (0.54%), octadecanoic acid (73.75%), palmitoleic acid (0.31%), and 11-eicosenoic acid (0.15%).

In this study, oil was extracted from Calabash seeds and subsequently converted into biodiesel. The biodiesel production process involved variations of acid and base catalysts. The resulting biodiesel products were further characterized to assess their quality.

Method

Materials and Equipment

The equipment used in this study included a mortar, beakers (Pyrex), Erlenmeyer flasks (Pyrex), analytical balance (Ohaus), oven (Shell Lab), hotplate (Cimarex), a Soxhlet extraction apparatus (Pyrex), round-bottom flasks (Pyrex), GC-MS (Shimadzu), three-neck flasks (Pyrex), separatory funnel (Pyrex), and evaporator (Rotavapor R-215 Buchi). The materials used included *Crescentia cujete* (Calabash) seeds, n-hexane (pa., Merck), methanol (pa., Merck), nitric acid (HNO_3, pa., Merck), and sulfuric acid (H_2SO_4, pa., Merck).

Sample Preparation

A total of 1 kg of *Crescentia cujete* seeds were thoroughly washed with water and sun-dried. The seeds were then heated at 80 °C to remove any residual moisture.

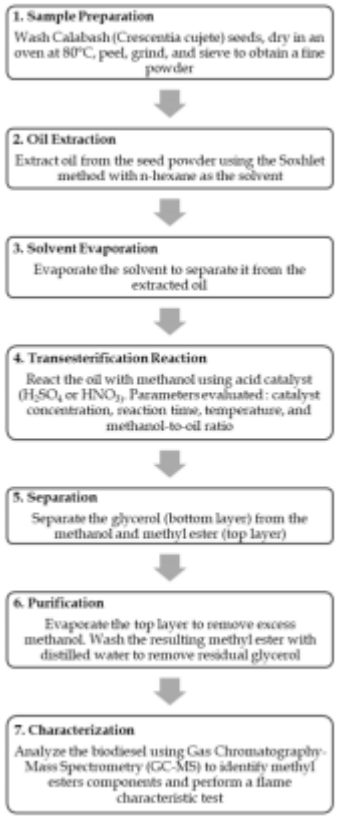

Figure 1. Research flowchart

Sample Extraction

The dried seeds were ground into fine powder to increase surface area and facilitate extraction. The powder was placed into the Soxhlet extractor lined with filter paper and extracted using n-hexane (1:3 w/w) at around 70 °C. The resulting oil was separated from n-hexane using a rotary evaporator set at 69 °C, yielding crude *Crescentia cujete* seed oil.

Biodiesel Synthesis Using Acid Catalysts

Approximately 2 g of crude seed oil was placed into a three-neck flask, followed by the addition of methanol at a molar ratio of 1:9 (oil:methanol). Sulfuric acid (H_2SO_4) was added as a catalyst at concentrations of 1%, 2%, 3%, 4%, and 5% (w/w) relative to the oil–methanol mixture. The mixture was then refluxed at varying temperatures of 50, 55, 60, 65, and 70 °C for reaction durations of 2, 3, 4, 5, and 6 hours. Upon completion, the mixture was cooled and transferred into a separatory funnel to separate the glycerol (bottom layer) from the methanol and methyl ester (top layer). The top layer was evaporated to remove excess methanol, and the resulting methyl ester was washed with distilled water to remove residual glycerol. The ester layer was then

dried using anhydrous sodium sulfate (Na_2SO_4), followed by filtration with Whatman No. 42 filter paper. The final biodiesel product was characterized using GC-MS and subjected to flame characteristic analysis. The same procedure was repeated using nitric acid (HNO_3) as the acid catalyst.

Biodiesel Characterization

Characterization of the biodiesel was conducted using gas chromatography–mass spectrometry (GC-MS) and flame characteristic tests. The summary of this procedure can be seen in Figure 1.

Result and Discussion

Sample Preparation

Calabash seeds were obtained from the pulp of the *Crescentia cujete* fruit (Figure 2). The seeds were thoroughly washed with water to remove any remaining fruit pulp, and subsequently dried in an oven at 80 °C for 24 hours.

Figure 2. Calabash fruit

Sample Extraction

The dried Calabash seeds were ground to increase the surface area, thus improving the contact between the solvent and sample and facilitating a more efficient oil extraction. The extraction was carried out using the Soxhlet method, which is effective in isolating oil content from the seed material with n-hexane as the solvent. The powdered sample was wrapped in filter paper and placed inside the Soxhlet extractor. After the extraction process, the mixture was subjected to evaporation to separate the solvent from the oil. The oil yield from this Soxhlet extraction process was 35.20%. The steps of the extraction process are illustrated in Figure 3.

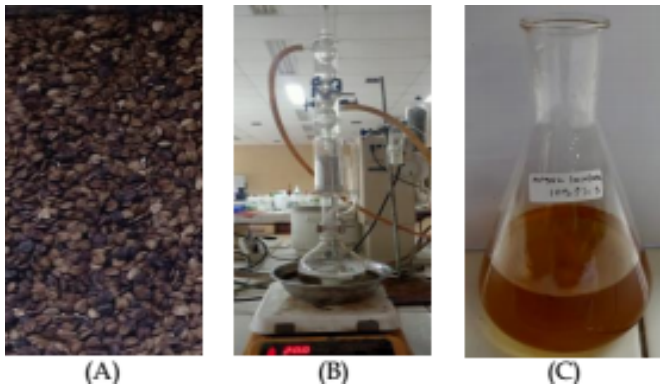

Figure 3. (A) Dried calabash seeds, (B) Soxhlet extraction, (C) Calabash seed oil

Biodiesel Synthesis Using Acid Catalysts

The transesterification reaction occurs between triglycerides and alcohol, aiming to convert fatty acids from triglycerides into methyl esters. This reaction is essentially an alcoholysis process, which proceeds very slowly without a catalyst (Muhali et al., 2023; Malabadi et al., 2023; Sk et al., 2016; Muhali et al., 2023). Acid catalysts are advantageous due to their tolerance toward high levels of free fatty acids (FFA) present in raw materials (Nabgan et al., 2022).

Biodiesel was synthesized via acid-catalyzed transesterification. The extracted oil was reacted with methanol in the presence of an acid catalyst. Two types of acid catalysts were used: H_2SO_4 and HNO_3. The reaction yielded two layers: the upper layer containing methanol and methyl ester, and the bottom layer consisting of glycerol. The lower layer was removed, and the upper layer was washed with distilled water to separate residual impurities, forming two new layers: water at the bottom and methyl ester at the top. The top layer was then separated, dried with anhydrous Na_2SO_4 to remove any remaining moisture, and filtered. The synthesis process was influenced by various parameters including catalyst concentration, reaction time, temperature, and methanol-to-oil ratio.

Determination of Optimum Catalyst Weight

To examine the effect of catalyst weight on biodiesel yield, controlled variables included reaction time (2 hours), temperature (65 °C), and methanol-to-oil ratio (1:9), while the catalyst concentration was varied at 1%, 2%, 3%, 4%, and 5% by weight of the oil/methanol mixture. These variations were intended to determine the optimal catalyst concentration that produces the highest biodiesel yield. The results indicated that the optimum concentration for H_2SO_4 was 4%, and for HNO_3 was 3%, yielding 62.11% and 19.00% biodiesel respectively. The biodiesel yields for each acid catalyst concentration are presented in Table 1.

Table 1. Biodiesel Yield (%) at Different Catalyst Concentrations for H_2SO_4 and HNO_3

Catalyst Ratio to Oil-Methanol (%)	Biodiesel Yield (%)	
	H_2SO_4	HNO_3
1	20.38	12.06
2	21.24	16.52
3	30.21	19.00
4	62.12	18.90
5	33.53	18.01

The relationship between catalyst concentration and biodiesel yield for two types of acid catalysts is illustrated in Figure 4. The graph shows a significant increase in biodiesel yield with increasing concentrations of H_2SO_4 catalyst. The yield increased from 1% to 3% catalyst concentration and reached its maximum at 4%. A decrease in biodiesel yield was observed at 5% concentration.

In contrast, the results obtained using HNO_3 followed a slightly different trend. The biodiesel yield increased from 1% to 3%, reaching its optimum at 3%, followed by a decline in yield at 4% and 5% concentrations.

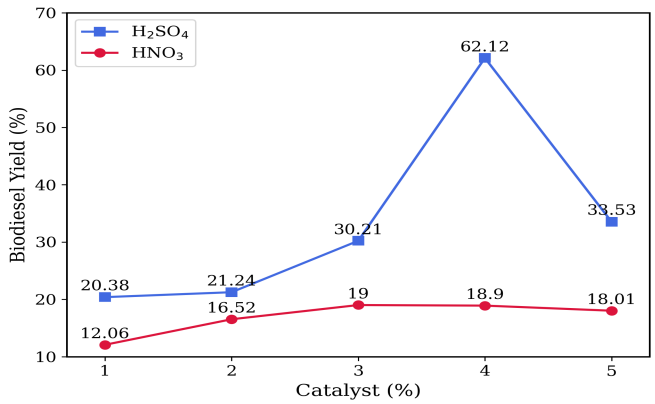

Figure 4. Effect of catalyst concentration on biodiesel conversion (%)

The results indicate that increasing catalyst concentration enhances biodiesel conversion up to an optimum point. This is because higher catalyst concentrations reduce the activation energy, thereby facilitating more effective conversion of triglycerides to methyl esters (Feyzi et al., 2017). However, beyond a certain point, excess catalyst can increase the viscosity of the reaction mixture, reducing mixing efficiency and ultimately lowering the yield (Mohammed et al., 2023).

Determination of Optimum Reaction Time

The optimum reaction time for biodiesel synthesis was determined using the previously identified optimum catalyst concentrations: 4% H_2SO_4 and 3% HNO_3. The synthesis was conducted at a temperature of 65 °C with an oil-to-methanol ratio of 1:9, and reaction times of 2, 3, 4, 5, and 6 hours were tested to determine the optimal duration for each acid catalyst.

The results showed that the optimum reaction time for H_2SO_4 was 4 hours, producing a biodiesel yield of 76.19%. For HNO_3, the optimum reaction time was 6 hours, yielding 65.85% biodiesel. The biodiesel yield for each catalyst at varying reaction times is presented in Table 2.

Table 2. Biodiesel Yield (%) at Different Reaction Times for H_2SO_4 and HNO_3

Time (hours)	Biodiesel Yield (%)	
	H_2SO_4	HNO_3
2	62.12	19.00
3	65.64	27.99
4	76.19	33.86
5	71.98	64.84
6	65.31	65.85
7	-	39.75

Figure 5 shows the effect of reaction time on the percentage of biodiesel produced. The graph indicates that the longer the reaction time, the higher the percentage of biodiesel yield. The optimum reaction times for the conversion of triglycerides into biodiesel using H_2SO_4 and HNO_3 catalysts were 4 and 6 hours, respectively. Reaction duration plays a significant role in determining the yield, as a longer reaction time provides more contact time for collisions between reactant particles (Darnoko & Cheryan, 2000; Munir et al., 2020).

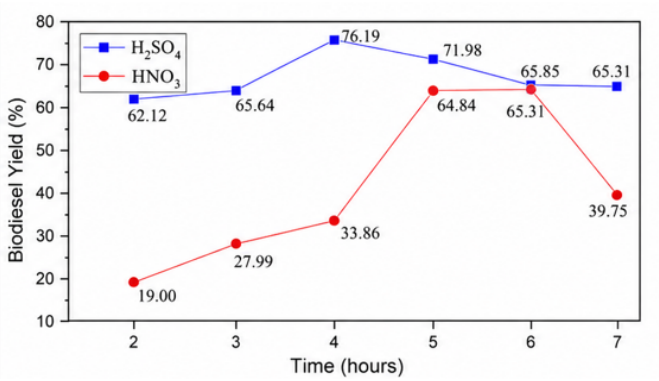

Figure 5. Effect of reaction time on biodiesel conversion percentage

Determination of Optimum Temperature

The variables used for determining the optimum temperature were the optimum catalyst weight and reaction time obtained from previous experiments. The ratio of H_2SO_4 catalyst to oil weight was 4% with a reaction time of 4 hours, while for HNO_3 it was 3% with a reaction time of 6 hours. The temperature variations used were 50, 55, 60, 65, and 70 °C for both acids. The results showed that the optimum temperature for both catalysts was 65 °C, with the resulting biodiesel yields of 76.19% for H_2SO_4 and 65.85% for HNO_3. Table 3 shows the temperature variation data along with the corresponding biodiesel yields for both acid catalysts.

Table 3. Optimum Temperature Data for the Two Acid Catalysts

Temperature (^{0}C)	Biodiesel Yield (%)	
	H_2SO_4	HNO_3
50	29.20	16.55
55	45.26	25.37
60	49.30	30.81
65	76.19	65.85
70	75.88	43.57

Figure 6 shows that temperature significantly affects biodiesel conversion for both catalysts. As the temperature increases, the biodiesel yield also increases. According to Nabgan et al. (2022), higher reaction temperatures can accelerate the reaction rate and reduce oil viscosity, resulting in a higher biodiesel yield.

As the reaction temperature increases, the frequency of molecular collisions also increases, leading to higher biodiesel production. However, as shown in Figure 5, the biodiesel yield decreases at 70 °C for both acids. This may be due to the evaporation of methanol from the system, as the reactor could not retain it, resulting in less effective collisions and thus lower product yield (Feyzi et al., 2017).

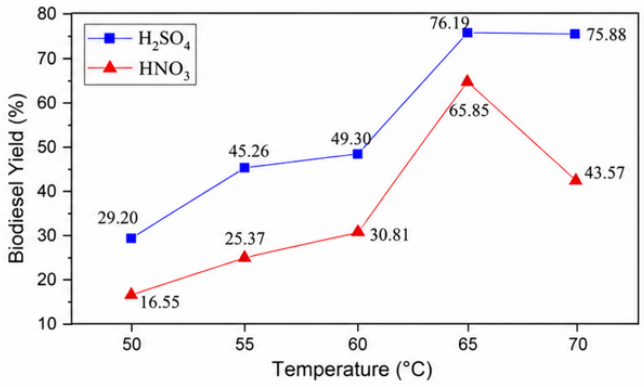

Figure 6. Effect of temperature on biodiesel conversion percentage

Determination of Optimum Oil/Methanol Ratio

The variables used in determining the optimum oil/methanol ratio were based on the optimum conditions obtained from previous treatments. For H_2SO_4: catalyst ratio 4%, temperature 65 °C, and reaction time 4 hours. For HNO_3: catalyst ratio 3%, temperature 65 °C, and reaction time 6 hours. The oil/methanol ratios tested were 1:3, 1:6, 1:9, 1:12, and 1:15.

The results showed that the optimum oil-methanol ratio for H_2SO_4 was 1:12 with a biodiesel yield of 91.20%, while for HNO_3 the best ratio was 1:9 with a yield of 65.85%. The data for oil-methanol ratio variations are shown in Table 4. Figure 7 shows that the biodiesel conversion value continues to increase as the methanol-to-oil ratio increases. This is because esterification is an equilibrium reaction; when one of the reactants is in excess, the reaction shifts toward the product side, increasing the frequency of collisions between molecules, resulting in higher biodiesel conversion (Satriadi, 2015). However, increasing the methanol-to-oil ratio can also inhibit the conversion of protonated free fatty acids at the active sites (Cerón Ferrusca et al., 2023; Park et al., 2016; Sangar et al., 2019).

Table 4. Optimum Oil/Methanol Ratio Data for Two Acid Catalysts

Oil/Methanol Ratio	Biodiesel Yield (%)	
	H_2SO_4	HNO_3
1:3	28.30	4.34
1:6	48.59	31.81
1:9	76.19	65.85
1:12	91.20	57.71
1:15	74.23	49.10

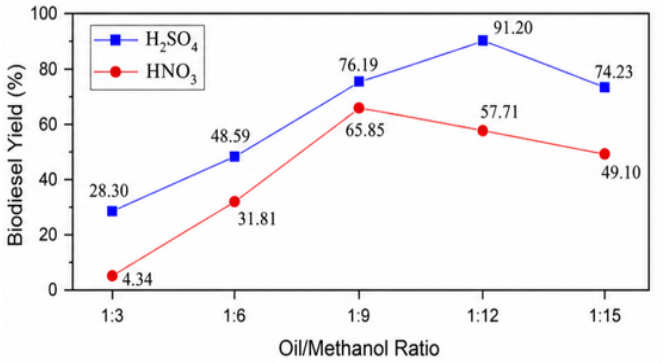

Figure 7. Effect of methanol-to-oil ratio on biodiesel conversion percentage

Negm et al. (2018) reported that methanol acts as an emulsifier, and excess methanol increases the viscosity of the mixture, thereby hindering the formation of methyl esters. However, this effect has a limit, beyond which additional methanol no longer significantly impacts the biodiesel yield. In this study, the optimum oil-to-methanol ratio was found to be 1:12 for H_2SO_4 and 1:9 for HNO_3.

It can be observed in each optimization result that the biodiesel yield obtained using H_2SO_4 catalyst is higher due to its better catalytic properties compared to HNO_3 (Arimami et al., 2015). Meanwhile, both acid catalysts yield higher biodiesel than the base catalyst, which obtained 61.33%, as reported by Adeyemi et al. (2023). The catalytic activity of nitric acid is lower because it tends to cause oxidative cleavage of methyl fatty acid esters (Park et al., 2016), resulting in lower product formation. In contrast, sulfuric acid has better catalytic activity because each molecule of sulfuric acid can facilitate the protonation step twice as often. This increases the affinity of the carbonyl binding in triglycerides with the oxygen atom of methanol, thereby increasing the amount of product formed (Chen et al., 2026).

Biodiesel Characterization

GC-MS Analysis of Pumpkin Seed Oil Biodiesel

GC-MS analysis of biodiesel aims to identify the types of methyl esters present in the biodiesel. The chromatogram data of pumpkin seed oil biodiesel from both acid catalysts showed similar compound area percentages. The chromatogram data of methyl esters from H_2SO_4 and HNO_3 catalysts are shown in Figures 8 and 9 and detailed in Tables 5 and 6.

Based on GC data using H_2SO_4 as a catalyst, there were 24 peaks observed, consisting of 7 types of methyl ester compounds and 15 other compounds. In comparison, the GC data using HNO_3 as a catalyst also showed 24 peaks, consisting of 8 types of methyl ester compounds and 14 other compounds. However, both catalysts share three methyl ester compounds with the highest area percentages.

The three compounds with the highest area percentages for the H_2SO_4 catalyst were methyl hexadecanoate or methyl palmitate (16.93%), methyl octadecanoate or methyl stearate (15.07%), and methyl 9-octadecenoate or methyl oleate (43.64%). Meanwhile, the compounds with the highest area percentages using HNO_3 as a catalyst were methyl hexadecanoate or methyl palmitate (16.55%), methyl octadecanoate or methyl stearate (26.90%), and methyl 9-octadecenoate or methyl oleate (21.51%). The chromatogram peak of Calabash oil using sulfuric acid as a catalyst with a retention time of 21.497 minutes was produced by methyl palmitate.

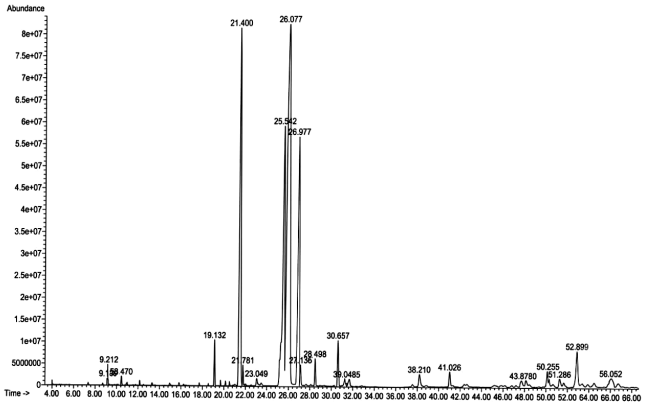

Figure 8. Chromatogram of pumpkin seed oil biodiesel (methyl esters) using H_2SO_4 catalyst

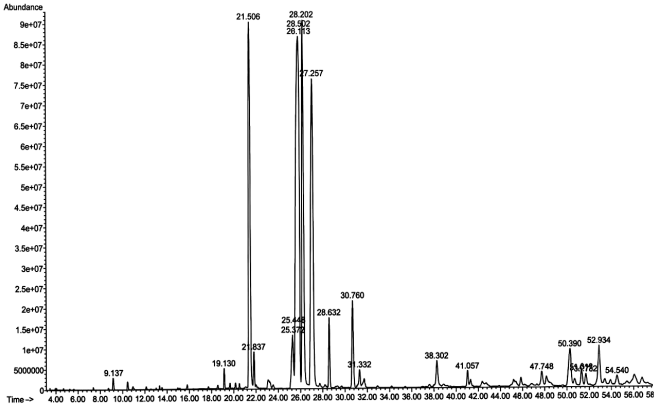

Figure 9. Chromatogram of calabash seed oil biodiesel (methyl esters) using HNO_3 catalyst

Table 5. Methyl Ester Components of Calabash Seed Oil Using H_2SO_4 Catalyst

Compound Name	Molecular Formula	Retention Time (minutes)	% Area
Methyl hexadecanoate	$C_{17}H_{34}O_2$	21.497	16.93
Methyl octadecanoate	$C_{19}H_{38}O_2$	25.593	15.07
Methyl 9-octadecenoate	$C_{19}H_{36}O_2$	26.076	43.64
Methyl 9-cis,11-trans-octadecadienoate	$C_{19}H_{34}O_2$	26.979	12.76
Methyl eicosanoate	$C_{21}H_{42}O_2$	30.654	1.47
Methyl 9-octadecanoate	$C_{19}H_{36}O_2$	52.898	2.22
Methyl 9,12-octadecadienoate	$C_{19}H_{34}O_2$	56.050	1.05

Table 6. Methyl Ester Components of Pumpkin Seed Oil Using HNO_3 Catalyst

Compound Name	Molecular Formula	Retention Time (minutes)	% Area
Methyl hexadecanoate	$C_{17}H_{34}O_2$	21.594	16.55
Methyl octadecanoate	$C_{19}H_{38}O_2$	25.959	26.90
Methyl 9-octadecenoate	$C_{19}H_{36}O_2$	26.110	21.51
Methyl 6-octadecenoate	$C_{19}H_{36}O_2$	26.400	7.45
Methyl 9-octadecenoate	$C_{19}H_{36}O_2$	27.255	16.05
Methyl 9,12,15-octadecatrienoate	$C_{19}H_{32}O_2$	28.634	1.18
Methyl eicosanoate	$C_{21}H_{42}O_2$	30.771	1.96
Methyl 9-octadecenoate	$C_{19}H_{36}O_2$	52.933	1.58

The mass spectrum of this methyl ester is shown in Figure 10. The mass spectrum indicates that the methyl palmitate compound ($C_{17}H_{34}O_2$) has a molecular ion peak at m/z = 270. This result is consistent with the molecular weight of palmitic acid (270 g/mol),

supported by the estimated fragmentation pattern (Figure 11).

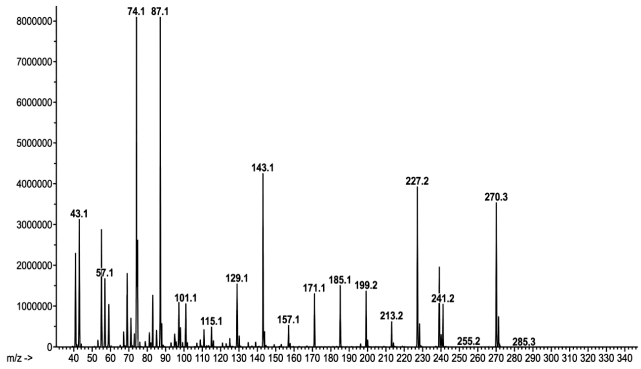

Figure 10. Mass spectrum of methyl palmitate

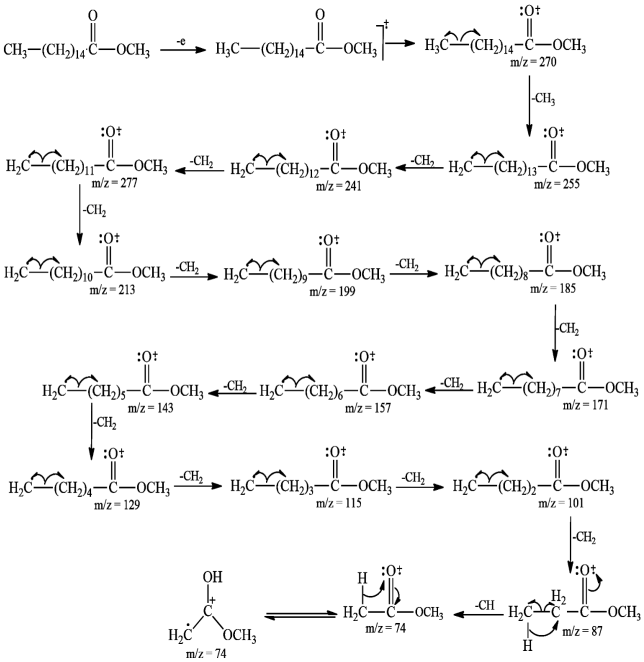

Figure 11. Fragmentation pattern of methyl palmitate

The fragment pattern shows a peak at m/z = 255 resulting from the loss of a methyl group (-CH_3), a peak at m/z = 241 from the loss of a CH_2 radical, followed by peaks at m/z = 227, 213, 199, 185, 171, 157, 143, 129, 115, 101, and 87—all resulting from the successive loss of CH_2 radicals. The peak at m/z = 74 is the base peak produced by the loss of a CH radical. Peaks with m/z values higher than the molecular weight of methyl palmitate (270 g/mol), such as m/z = 285, are caused by noise. Noise refers to molecular ions with a relative abundance of less than 1% (Amirav & Yakovchuk, 2023).

The chromatogram peak of Calabash oil using acid catalyst with a retention time of 25.593 minutes was produced by methyl stearate. The mass spectrum of this methyl ester is presented in Figure 12. The mass spectrum shows that the methyl stearate compound ($C_{18}H_{36}O_2$) has a molecular ion peak at m/z = 298. This result is consistent with the molecular weight of stearic acid (298 g/mol), and is supported by the estimated fragmentation pattern (Figure 13).

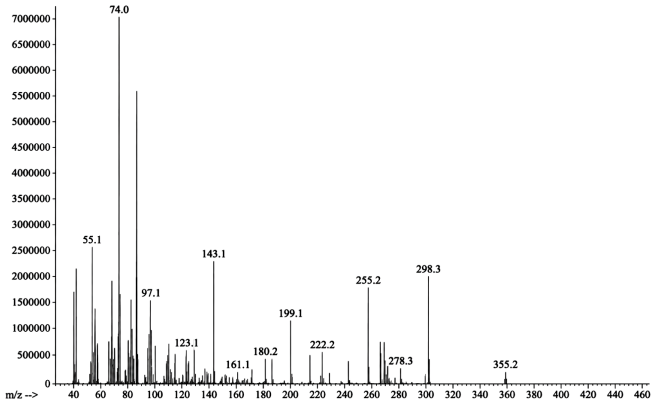

Figure 12. Mass spectrum of methyl stearate

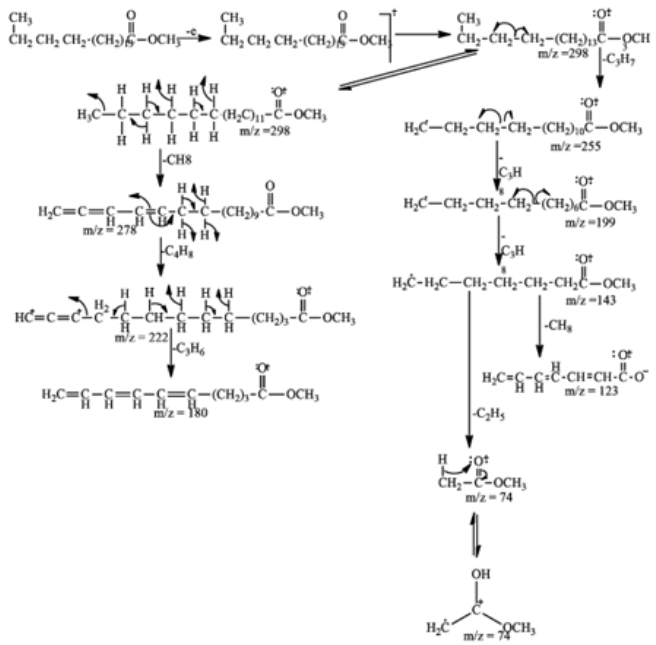

Figure 13. Fragmentation pattern of methyl stearate

The fragmentation pattern with a peak at m/z = 255 is the result of the loss of a C_3H_7 ion. The peak at m/z = 199 results from the loss of a C_3H_8 radical, while the peak at m/z = 143 is also due to the loss of a C_3H_8 radical. The peak at m/z = 74 is the base peak resulting from the loss of a C_2H_5 radical. Several peaks follow different fragmentation pathways, such as the peak at m/z = 278 from the loss of a CH_8 ion, m/z = 222 from the loss of C_4H_8, and m/z = 180 from the loss of C_3H_6. Mass spectra with m/z values exceeding the molecular weight of methyl stearate (298 g/mol), such as m/z = 355, are attributed to noise. Noise refers to molecular ions that appear with relative abundance below 1% (Amirav & Yakovchuk, 2023). The chromatogram peak

of pumpkin seed oil using acid catalyst with a retention time of 26.076 minutes corresponds to methyl oleate.

The mass spectrum of the methyl ester is shown in Figure 14. The spectrum shows that the compound methyl oleate ($C_{18}H_{34}O_2$) has a molecular ion peak at m/z = 296, consistent with the molecular weight of oleic acid (296 g/mol), and is supported by the predicted fragmentation pattern shown in Figure 15.

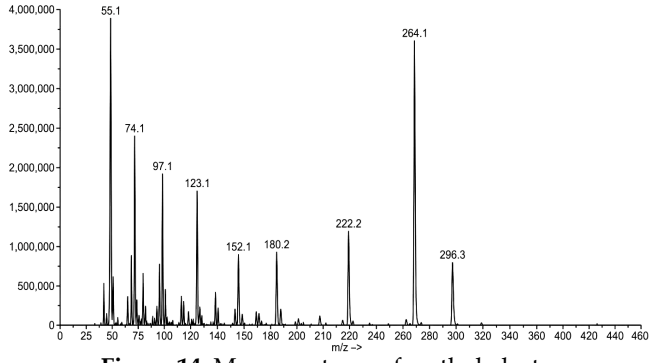

Figure 14. Mass spectrum of methyl oleate

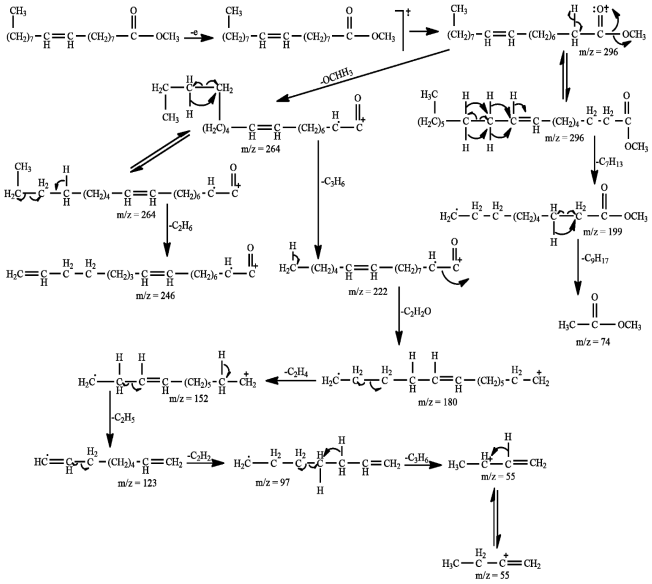

Figure 15. Fragmentation pattern of methyl oleate

The fragmentation pattern shows a peak at m/z = 264 from the loss of a (-OCH_3) ion, m/z = 222 from the loss of C_3H_6, m/z = 180 from the loss of a C_2H_2O radical, m/z = 152 from the loss of a C_2H_4 radical, m/z = 123 from the loss of a C_2H_5 radical, and m/z = 97 from the loss of a C_2H_2 radical. The peak at m/z = 55 is the base peak resulting from the loss of a C_3H_6 radical. Several other peaks follow different fragmentation pathways, such as the peak at m/z = 246 from the loss of C_2H_6, m/z = 199 from the loss of a C_7H_{13} ion, and m/z = 74 from the loss of a C_9H_{17} radical. Similar to the previous spectrum, mass spectral peaks with m/z values exceeding the molecular weight of methyl oleate (296 g/mol), such as m/z = 319, are due to noise, which represents molecular ions with relative abundance below 1% (Amirav & Yakovchuk, 2023).

Flame Characterization Test of Biodiesel

The biodiesel obtained after the reflux process was separated for flame testing to determine its combustion characteristics. A total of 4 mL of biodiesel was placed in the test apparatus to observe its flame behavior. The results showed that the flame color of biodiesel produced using both acid catalysts ranged from orange to blue, with differing flame durations. The biodiesel produced with nitric acid catalyst burned for 40 minutes, while the one with sulfuric acid catalyst burned for 60 minutes. Flame visualizations of biodiesel combustion are presented in Figures 16 and 17.

Figure 16. Flame Visualization of Biodiesel with Nitric Acid Catalyst

Figure 17. Flame Visualization of Biodiesel with Sulfuric Acid Catalyst

The height of the flame gradually decreased over time. This occurred due to the diminishing volume of biodiesel consumed during the combustion process. When a larger amount of biodiesel is used, the flame becomes more fluctuating and shorter (Arnif, Budianto, & Cahyadi, 2019). The calculated combustion rate or flame propagation rate of biodiesel was 1.96 x 10^{-3} cm^2/s for H_2SO_4 catalyst and 2.71 x 10^{-3} cm^2/s for HNO_3 catalyst (Appendix 5). Based on the combustion rate, the biodiesel produced using H_2SO_4 catalyst demonstrated better flame characteristics than that produced with HNO_3 catalyst, as a lower combustion rate corresponds to a longer flame duration (Rahardja et al., 2021).

Conclusion

Based on the findings of this study, *Crescentia cujete* seed oil was successfully extracted by the Soxhlet method with an oil yield of 35.20% and demonstrated its potential as a non-edible feedstock for biodiesel production. The transesterification process confirmed that sulfuric acid outperformed nitric acid as an acid catalyst, producing the highest biodiesel yield (91.20%) under optimum conditions of 4% catalyst loading, 65 °C, 4 h, and an oil-to-methanol molar ratio of 1:12, whereas

nitric acid produced 65.85% biodiesel at 3% catalyst loading, 65 °C, 6 h, and a molar ratio of 1:9. GC-MS analysis identified seven and eight methyl ester compounds in the biodiesel produced using sulfuric and nitric acid catalysts, respectively, confirming successful biodiesel formation. The combustion rates were 1.96 × 10^{-3} cm^2/s for sulfuric acid-derived biodiesel and 2.71 × 10^{-3} cm^2/s for nitric acid-derived biodiesel, indicating better combustion characteristics for biodiesel produced using sulfuric acid. Overall, sulfuric acid proved to be the more effective catalyst for biodiesel production from *C. cujete* seed oil, providing higher biodiesel yield, shorter reaction time, and improved fuel performance.

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Author Contributions
NG, MFJDPT and CMP conceptualized the research. NG and CMP performed the methodology, data collection, investigation, and data curation. MFJDP performed the data analysis, and data visualization. CMP, MS, and PMP prepared the writing – original draft and contributed to writing – review and editing, as well as project administration. NG and MFJDPT provided resources, validation, supervision, and funding acquisition, and contributed to writing – review and editing. All authors contributed to and approved the final version of the manuscript.

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Conflict of Interest
The authors declare that the research was conducted without any commercial or financial relationships that could potentially create a conflict of interest.

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