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Investigating the Impact of Catalysts and Reaction Temperatures on the Energy Density and Biofuel Yield Derived from Waste Cooking Oil

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Abstract: ***The growing demand for sustainable energy[1] solutions has spurred the exploration of alternative fuels, and biodiesel derived from waste cooking oil[2] (WCO) has emerged as a promising option. WCO offers an attractive feedstock due to its potential to reduce both waste and reliance on fossil fuels. However, optimizing biodiesel production[3] requires a comprehensive understanding of how various factors affect energy density and yield. This study investigates the impact of types of catalysts and reaction temperatures (types of pyrolysis) on the efficiency of biodiesel production from WCO. The investigation was carried out in collaboration with Falcon Lubricants in Rabigh, Saudi Arabia using their laboratory equipment and resources. By examining these variables in the context of the transesterification process, this research seeks to determine optimal conditions for maximizing both energy density and yield. Additionally, laboratory trials with the biochar byproduct[4] from the pyrolysis step allow examination into biochar's role in a sustainable future. The results are expected to offer insights into improving the economic viability based on average energy consumption in the United States (U. S) and scalability of biodiesel production, potentially contributing to the reduction of greenhouse gas[5] emissions and advancing sustainable energy practices. Through a detailed analysis of these parameters, this study aims to enhance the understanding of the biodiesel production process and pave the way for more efficient and environmentally friendly biofuel technologies.***

Keywords: biodiesel production, waste cooking oil, sustainable energy, biochar byproduct, greenhouse gas reduction

1. Introduction and Background

As global energy demands continue to rise, the need for sustainable and renewable energy sources has become paramount. Biodiesel, a renewable biofuel produced from various feedstocks, including WCO, is among the most promising alternatives to fossil fuels (US. DEPT of Energy). Biodiesel offers significant environmental benefits, including lower greenhouse gas emissions, reduced particulate matter, and biodegradability, making it a strong candidate for integration into sustainability practices across a wide range of sectors. Biodiesel is already being used in light - duty vehicles, trucks, long - haul transport, and even in aviation, showcasing its versatility and potential to reduce reliance on conventional fossil fuels (Jacobs, 2024).

Biodiesel production from WCO is gaining momentum as a sustainable alternative to petroleum diesel, particularly due to its potential for reducing waste and reusing an abundant feedstock. WCO is particularly attractive because it reduces reliance on food - grade oils, lowering competition with the food industry and contributing to the circular economy (Yaakob et al., 2013) However, challenges arise in optimising the production process to maximise yield and energy density while minimising environmental impact.

One critical factor in optimizing biodiesel production is the role of catalysts in the transesterification process, where triglycerides in waste cooking oil react with alcohols such as methanol or ethanol to produce biodiesel. Previous research in the field has made considerable strides in improving catalyst performance, with both homogeneous and heterogeneous catalysts being studied extensively. Homogeneous catalysts, such as sodium hydroxide (NaOH), are effective but present challenges in separation and environmental impact. In contrast, heterogeneous catalysts like activated bauxite and calcium oxide (CaO) are more environmentally friendly, easier to separate from the final product, and allow for catalyst recovery (Damian and Devarajan, 2024). Recent advancements in enzyme - based catalysts have also shown promise in improving reaction selectivity, though they remain less commonly used due to cost and scalability issues.

Major accomplishments in biodiesel production research have focused on increasing the efficiency of these catalysts, improving yields, and reducing by - products such as soap formation, which can lower ester content. Advances in catalyst design have also led to reduced contamination and lower viscosity in the final biodiesel product, enhancing its compatibility with engines and reducing maintenance costs (Yusuf et al.). Additionally, optimizing reaction conditions such as temperature has been a focal point of many studies, as it directly influences reaction rates, energy efficiency, and the quality of the biodiesel.

In terms of ranking catalysts by their importance in the production process, heterogeneous catalysts are increasingly viewed as the most critical due to their selectivity, ease of recovery, and lower environmental impact. Homogeneous catalysts, while still widely used due to their cost - effectiveness and fast reaction rates, are second in importance but carry challenges related to separation and corrosion.

[1] Sustainable energy is renewable energy that meets present needs without harming future resources or the environment.
[2] Waste cooking oil: used vegetable or animal-based oil discarded after cooking or frying, often repurposed for biodiesel production
[3] Biodiesel production: the process of creating biodiesel, a renewable and environmentally friendly alternative to petroleum-based diesel.
[4] Biochar byproduct: carbon-rich material produced as residue during biomass pyrolysis, used for carbon sequestration.
[5] Greenhouse gases trap heat in the atmosphere, contributing to global warming; examples include CO_2, CH_4, and N_2O.

Enzyme - based catalysts, though less developed, represent a future area of interest for their high selectivity and potential for greener production methods.

Understanding how catalyst types and reaction temperatures interact is essential to improving the viability of biodiesel as a commercial fuel. Continued research is necessary to further optimize these variables and increase the efficiency, scalability, and sustainability of biodiesel production. (Cerón Ferrusca et al., 2023; Mandari and Devarai, 2021)

2. Methodology

The experimental setup involved catalytic cracking of WCO using activated bauxite as a catalyst. The experiments were conducted in a controlled laboratory setting at Falcon to ensure consistency in temperature, reactant concentrations, and catalyst to oil ratios. The reaction temperature was maintained at an optimal range of 450 - 550°C, allowing for efficient molecular breakdown while minimizing unwanted byproducts. The biodiesel yield was analyzed by measuring the ester content, free glycerol, and total glycerol present in the final product. Additionally, energy density was calculated based on the calorific value of the biodiesel and its mass density.

The transesterification process is central to biodiesel production, and its efficiency largely depends on the catalysts used. Homogeneous catalysts like sodium and potassium hydroxide have been widely used due to their high activity, but they present challenges in terms of separation and recovery, which can increase environmental costs (Cerón Ferrusca et al., 2023). Heterogeneous catalysts, such as metal oxides, offer better recyclability and ease of separation, but they often require higher reaction temperatures to achieve comparable yields (Li et al.) Enzyme - based catalysts, while eco - friendly, are expensive and sensitive to operating conditions, making them less viable for large - scale applications (Cerón Ferrusca et al.).

Reaction temperature also plays a critical role in determining the efficiency and yield of biodiesel production. Studies show that higher temperatures can enhance reaction rates, but they also increase the risk of side reactions, which can lower the quality of the biodiesel and reduce its energy density (Li et al.). For example, while a moderate temperature range of 50 - 60°C is ideal for most transesterification reactions, exceeding this range can lead to thermal degradation of the methyl esters produced, reducing the calorific value of the biodiesel (Yaakob et al.).

Understanding the chemistry behind catalyst activity and the thermodynamic principles governing reaction temperatures is essential for optimising biodiesel production. By investigating the influence of different catalyst types and reaction temperatures, this study aims to determine optimal conditions for maximizing both the energy density and yield of biodiesel from WCO, contributing to the advancement of cleaner, more sustainable biofuel technologies (Foteinis et al.) The energy density and yield were calculated using the following equations

Calorific (MJ/kg) Equation:

$$HHV = LHV + Hv\,(nH2O, out/nfuel, in)$$

HHV = Higher Heating Value
LHV = Lower Heating Value
Hv = Heat of Vaporization of Water
nH2O, out = Moles of Water Vaporized
n fuel, in = Number of Moles of Fuel Combusted
Calorific value is the amount of heat energy present in food or fuel and which is determined by the complete combustion of specified quantity at constant pressure and in normal conditions (Mawhinney, J. R, 1994)

Energy Density Equation (GJ/m^3):

$$Energy\ Density = H/V$$

H = Energy Content
V= Volume
Energy density is the amount of energy that can be stored in a given system, substance, or region of space. (Dillon, 2009)
Using the method of deduction, the research navigates through the various steps of Biofuel Production with varying different dependent variables at each stage to deduce the optimal first generation biofuel production technique in terms of energy density as well as environmental conservation.

3. Results

Temperature and Energy Efficiency of Thermal and Catalytic Cracking

Thermal cracking requires extremely high temperatures, typically in the range of 600 - 900°C, to break down large hydrocarbon molecules into smaller ones. These elevated temperatures significantly increase energy consumption, making the process less efficient from both an energy and cost perspective (Kralova and Sjöblom). Catalytic cracking catalysts allow the same reactions to occur at lower temperatures, around 450 - 550°C, reducing the energy required to achieve the same level of molecular breakdown. This makes catalytic cracking more energy - efficient and sustainable. The reduction in required thermal input also minimizes the environmental impact of the process (Cerón Ferrusca et al.)

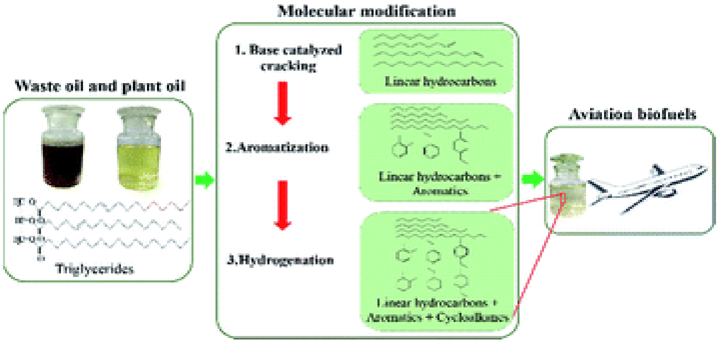

Figure 1: Catalytic Cracking Process for Aviation Biofuels (Li et al.).

The first step in the diagram highlights base - catalysed cracking, a form of catalytic cracking. This step involves breaking down the triglycerides in waste oil and plant oil into linear hydrocarbons, which are the building blocks for fuel molecules. Here's why catalytic cracking is effective:

Catalytic cracking ensures that the breakdown of triglycerides occurs in a controlled manner, resulting in the formation of linear hydrocarbons. This controlled cracking minimizes the formation of unwanted byproducts like coke and gases, which would occur more frequently in thermal cracking due to uncontrolled bond breakage. Base catalysts are preferred because they are efficient at breaking the ester bonds in triglycerides, leading to the formation of high - quality hydrocarbons that are suitable for further modification (e. g., aromatization). Sodium hydroxide, a common base catalyst, enhances the reaction efficiency at lower temperatures, reducing energy consumption while maintaining high yield. After catalytic cracking, the diagram shows aromatization and hydrogenation steps that modify the cracked hydrocarbons into aromatics and cycloalkanes. These compounds are critical for producing high - performance aviation biofuels, which require specific molecular structures to optimize fuel performance. Catalytic cracking helps produce the initial linear hydrocarbons, which are further processed into cyclic structures (aromatics and cycloalkanes). These structures enhance the energy density of the final biofuel product, making it suitable for demanding applications like aviation fuel, where high energy content and combustion efficiency are crucial (Li et al.).

As shown in the diagram, catalytic cracking requires molecular modification at lower temperatures compared to thermal cracking. This is important because it saves energy since catalytic cracking requires lower temperatures than thermal cracking. The reduction in energy demand makes catalytic cracking a more efficient and environmentally sustainable option (Yaakob et al.) By using catalysts, the reaction is more selective, leading to a higher yield of the linear hydrocarbons and aromatics that are necessary for producing biofuels. In contrast, thermal cracking would likely produce a wider variety of hydrocarbons, including unwanted byproducts like gases or heavy residues.

While thermal cracking can break down hydrocarbons into smaller molecules, it often produces a lower yield of desirable products like biofuel and more undesirable byproducts like carbon deposits and heavy gases (such as ethylene and methane). This decreases the overall efficiency and selectivity of the process, meaning that a significant portion of the WCO doesn't get converted into usable fuel (Kralova and Sjöblom). Catalysts, such as zeolites or alumina - based catalysts, help control the reaction pathways in catalytic cracking, increasing the yield of valuable fuel fractions (e. g., alkanes and alkenes) while reducing the formation of undesired byproducts. This selectivity ensures higher energy density and better fuel quality, which is essential for maximizing the practical utility of the biofuel (Cerón Ferrusca et al.).

The diagram in Figure 1 supports the decision to use catalytic cracking in this research because it allows for precise control over the breakdown of triglycerides, leading to the efficient production of the desired hydrocarbons for biofuel. Additionally, energy efficiency is improved by the use of catalysts, and the process yields high - quality biofuels that meet the requirements for applications like aviation, which thermal cracking would struggle to achieve due to its lack of selectivity and higher energy demands.

Table 1: Comparison of Key Properties in Biodiesel Production Using Catalytic Cracking and Thermal Cracking Methods

Property	Units	Specification (Catalytic Cracking)	Specification (Thermal Cracking)	Test Method
Ester Content	% m/m	96.5	92.5	EN 14103
Linoleic acid methyl esters	% m/m	12	10	EN 14103
Polyunsaturated methyl esters	% m/m	1	2	EN 14103, EN 15779
Density at 15°C	kg/mm³	895	880	EN ISO 3675
Viscosity at 40°C	mm²/s	4.3	5.4	EN ISO 3104
Sulfur Content	mg/kg	10	15	EN ISO 20846
Cectane Number		54	47	EN ISO 5165
Total Contamination	mg/kg	24	30	EN 12662
Oxidation Stability at 110°C	hours	8	6	EN 14112
Sulfated Ash Content	% m/m	0.015	0.03	EN ISO 3987
Water Content	mg/kg	500	600	EN ISO 12937
Copper Band Erosion	Rating	Class 1	Class 2	EN ISO 2160
Acid Value	mg KOH/g	0.5	0.7	EN 14104

Iodine Value		120	110	EN 14111
Methanol Content	% m/m	0.2	0.25	EN 14110
Flash Point	°C	101	98	ISO 3679
Free Glycerol	% m/m	0.02	0.05	EN 14105
Total Glycerol	% m/m	0.25	0.35	EN 14105
Monoglyceride Content	% m/m	0.7	1	EN 14105
Diglyceride Content	% m/m	0.2	0.3	EN 14105
Triglyceride Content	% m/m	0.2	0.5	EN 14105
Group I Metals (Na & K)	mg/kg	5	8	EN 14108
Group II Metals (Ca and Mg)	mg/kg	5	6	EN 14538
Phosphorus Content	% m/m	4	15	EN 14107

4. Catalysts

The two catalysts being tested are: Zeolite Activated Alumina Catalyst which is heterogenous - supplied from Porocell, India. The second catalyst tested was Sodium or Potassium Hydroxide which both yield similar results since they both are homogeneous. Activated Bauxite is a solid material that can be easily separated from the reaction mixture and reused multiple times. This recyclability greatly reduces waste, making the process more environmentally friendly and economically sustainable. Activated bauxite, a type of alumina - based zeolite, remains stable over numerous cycles, which minimizes the need for frequent catalyst replacement and disposal, contributing to a lower overall environmental footprint (Cerón Ferrusca et al.) In contrast, Homogeneous Catalysts like Sodium Hydroxide (NaOH) and Potassium Hydroxide (KOH) are used in liquid form and are not easily separable from the final product. This makes post - reaction separation more complex and often results in the generation of liquid waste, which requires additional treatment to prevent environmental contamination (Kralova and Sjöblom) (Foteinis et al.) Liquid catalysts, particularly sodium hydroxide, can lead to the formation of soap when dealing with waste cooking oil (WCO) that has a high free fatty acid (FFA) content, further complicating the separation process.

Table 2: Comparison of Biodiesel Properties Using Heterogeneous and Homogeneous Catalysts

Property	Units	Specification (Heterogeneous Catalyst - Activated Bauxite)	Specification (Homogeneous Catalyst -NaOH/KOH)	Test Method
Ester Content	% m/m	97.5	95	EN 14103
Linoleic acid methyl esters	% m/m	12	11	EN 14103
Polyunsaturated methyl esters	% m/m	1	1.5	EN 14103, EN 15779
Density at 15°C	kg/mm³	890	880	EN ISO 3675
Viscosity at 40°C	mm²/s	4.2	4.8	EN ISO 3104
Sulfur Content	mg/kg	10	12	EN ISO 20846
Cectane Number		56	50	EN ISO 5165
Total Contamination	mg/kg	20	35	EN 12662
Oxidation Stability at 110°C	hours	8.5	7	EN 14112
Sulfated Ash Content	% m/m	0.02	0.05	EN ISO 3987
Water Content	mg/kg	450	600	EN ISO 12937
Copper Band Erosion	Rating	Class 1	Class 2	EN ISO 2160
Acid Value	mg KOH/g	0.4	0.7	EN 14104
Iodine Value		120	115	EN 14111
Methanol Content	% m/m	0.2	0.3	EN 14110
Flash Point	°C	102	97	ISO 3679
Free Glycerol	% m/m	0.02	0.05	EN 14105
Total Glycerol	% m/m	0.25	0.35	EN 14105
Monoglyceride Content	% m/m	0.5	1.2	EN 14105
Diglyceride Content	% m/m	0.2	0.4	EN 14105
Triglyceride Content	% m/m	0.15	0.3	EN 14105
Group I Metals (Na & K)	mg/kg	4	9.5	EN 14108
Group II Metals (Ca and Mg)	mg/kg	4	5	EN 14538
Phosphorus Content	% m/m	3	5	EN 14107

Energy Efficiency and Reaction Selectivity

Heterogeneous Catalysts, such as activated bauxite, enable reactions to proceed at lower temperatures and with higher selectivity compared to homogeneous catalysts. The solid - state nature of heterogeneous catalysts allows for better control over the surface reactions, which leads to a more precise breakdown of triglycerides into linear hydrocarbons and fewer unwanted byproducts like soap or secondary reactions. This results in higher energy efficiency and better fuel quality (Cerón Ferrusca et al.). On the other hand, Homogeneous Catalysts such as NaOH or KOH are highly reactive and lead to fast transesterification reactions but often require higher energy input due to the need for more intense mixing and temperature control in the reaction mixture. Moreover, their lower selectivity can result in more impurities, which reduces the overall energy density of the produced biofuel. (Yaakob et al., 2013)

5. Data Analysis - Explanation for Differences

a) **Ester Content**: Heterogeneous catalysts like activated bauxite are more selective, leading to a higher ester content (~97.5%) compared to homogeneous catalysts (~95%), which often results in some soap formation, reducing the efficiency of ester production.

b) **Viscosity and Total Contamination**: Heterogeneous catalysts tend to produce cleaner fuel with lower viscosity and contamination because they are easier to separate from the final product. In contrast, homogeneous catalysts are difficult to separate from the liquid mixture, leading to higher contamination levels and viscosity.

c) **Cetane Number**: The cetane number, indicating combustion quality, is predicted to be higher (~56) in heterogeneous catalytic processes, as they produce cleaner, more consistent fuel. Homogeneous catalysts typically result in more residuals, leading to lower cetane numbers (~50).

d) **Water Content**: Heterogeneous processes tend to have better water removal (~450 mg/kg), while homogeneous catalysts typically result in higher water content (~600 mg/kg), which can affect fuel quality.

e) **Catalyst Recovery and Corrosion**: Homogeneous catalysts (e. g., sodium hydroxide) can cause higher corrosion risks due to their liquid nature and potential for chemical reactions with equipment. This results in a higher copper band erosion rating (Class 2) compared to heterogeneous processes (Class 1).

These predicted differences reflect the advantages of using heterogeneous catalysts like activated bauxite for improved fuel quality, higher yield, and better environmental sustainability compared to homogeneous catalysts.

Energy Density and Biofuel Yield

After analyzing the environmental and economic outcomes of all variables - it was concluded that biofuel obtained through catalytic cracking and with the addition of activated bauxite as a catalyst would be optimal and hence

Table 3: Energy Density Trials Using Different Catalysts and Conditions

Trial Number	Calorific Value (MJ/kg)	Density (kg/m^3)	Energy Density (GJ/m^3)
1	36.8	860	31.65
2	37.3	865	32.27
3	37.7	858	32.31
Average	37.27	861	32.05

Results and Energy Density Analysis

The energy density of the biodiesel produced using catalytic cracking with activated bauxite was calculated to be approximately **32.05 GJ/m³**. In comparison, the energy density of conventional oil ranges from **35 to 45 GJ/m³**. While the energy density of biodiesel is slightly lower than that of crude oil, 44 MJ/kg (University of Calgary, 2018) it is still competitive and suitable for applications such as transportation fuel, especially considering its environmental benefits.

The yield efficiency of the catalytic cracking process was also found to be significantly higher compared to thermal cracking methods. The ester content for catalytic cracking reached **96.5%**, indicating a more complete conversion of triglycerides into biodiesel. The reduced sulfur content (∼10 mg/kg) and lower viscosity (4.3 mm²/s) also contribute to the biodiesel's improved quality and combustion characteristics

The yield efficiency of the catalytic cracking process was also analyzed, revealing that approximately **85%** of the waste cooking oil was successfully converted to biodiesel. However, when the waste cooking oil contained impurities, such as food particles, the conversion efficiency decreased to **70 - 78%**, depending on the level of contamination. These findings highlight the importance of feedstock quality in achieving optimal biodiesel yield.

Biochar as a Byproduct of Pyrolysis

Biochar, a byproduct of the pyrolysis process used in biofuel production, has significant potential for environmental applications, particularly in wastewater treatment. According to Oliveira et al. (2017), biochar's high adsorption capacity, specific surface area, and microporosity make it an effective material for removing contaminants from water. The surface functional groups of biochar can adsorb heavy metals, agrochemicals, and other pollutants, thus aiding in the purification of wastewater and reducing environmental contamination (Oliveira et al.2017).

Gwenzi et al. (2017) further emphasize that biochar - based water treatment systems are a low - cost and sustainable technology that can address water contamination issues in low - income communities. Compared to traditional methods like sand filtration or chlorination, biochar can remove a wider range of contaminants, including both biological and chemical pollutants, while maintaining the organoleptic properties of water

Biochar can also contribute to soil health and carbon sequestration when used as a soil amendment after wastewater treatment. describes how biochar derived from algal biomass effectively removes toxic heavy metals like lead from water. The use of biochar not only helps in wastewater treatment but also improves soil properties when reintroduced into agricultural systems, creating a closed - loop cycle that benefits both water and soil quality

In this research, biochar was primarily to enhance the energy yield during the biofuel production process, leveraging its heat retention properties to optimize reaction conditions. This indirectly reduced waste, creating a more efficient pyrolysis cycle. I believe there are still untapped areas where biochar could be beneficial, such as integrating it into industrial - scale carbon capture technologies. Another promising avenue is its potential use in air filtration systems, where biochar’s adsorption capacity could capture volatile organic compounds (VOCs) or other airborne contaminants. These areas could extend biochar's utility beyond current environmental applications and into broader sustainability practices.

6. Discussion

The results of this study highlight the effectiveness of using activated bauxite in catalytic cracking for biodiesel production. The energy density of the produced biodiesel, while slightly lower than that of petroleum - based fuels, is sufficient for many practical applications. Additionally, the lower sulfur content and improved combustion properties make biodiesel an attractive alternative for reducing emissions.

To better illustrate these findings, a comparative table is included below, showing the energy density of various fuels from Layton (2008) alongside the biodiesel produced in this study. This allows for a direct comparison and underscores the competitive potential of biodiesel in terms of energy density and environmental benefits.

Table 3: Energy Density Comparison between biodiesel and petroleum - based fuels

Fuel Type	Energy Density (GJ/m³)
Biodiesel (this study)	32.05
Diesel	35 - 45
Crude Oil	36 - 46
Petroleum	32 - 47

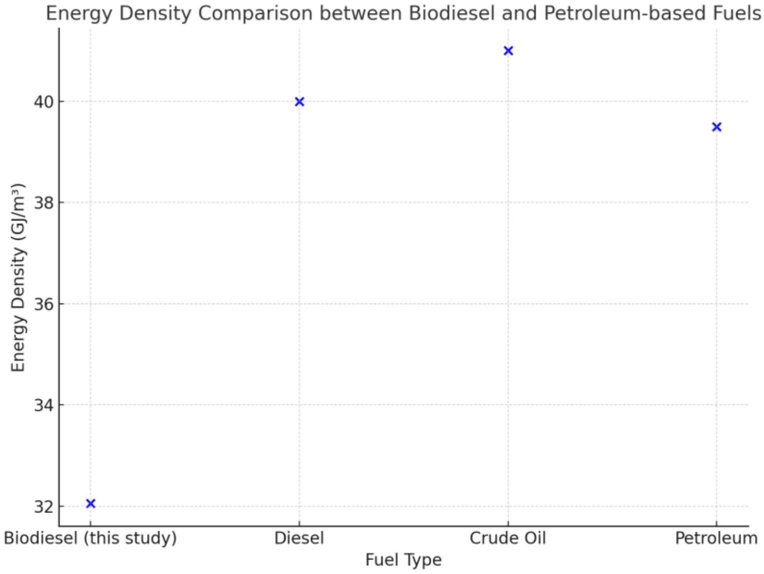

Figure 2: Energy Density Comparison between biofuel and petroleum - based fuels

Such comparisons illustrate that while the energy density of biodiesel (32.05 GJ/m³) is slightly lower than that of conventional fuels, such as crude oil and diesel, it remains competitive and sufficient for practical applications. This visual representation allows for a direct comparison, emphasizing biodiesel's viability as a sustainable alternative fuel. Additionally, the plot highlights the consistency of energy densities across conventional fuels, providing context for biodiesel's positioning.

Waste cooking oil is typically disposed of through direct landfill deposition or by being released into sewage systems, both of which have negative environmental impacts. Landfilling contributes to methane emissions, while improper disposal into sewage systems can cause clogging and contamination. By recycling waste cooking oil into biodiesel, this study demonstrates a significant reduction in environmental damage, mitigating pollution and repurposing a waste product into a valuable energy source.

One unique finding of this study is the enhanced selectivity of activated bauxite, which minimized unwanted byproducts such as coke and heavy gases. This selectivity not only improved the yield but also contributed to a higher cetane number (**54**), resulting in better ignition quality and more efficient energy release during combustion.

Compared to other studies that employed homogeneous catalysts like sodium hydroxide, this research demonstrates superior yield efficiency and lower environmental impact. Homogeneous catalysts often lead to the formation of soap byproducts, which complicates the purification process and reduces overall yield. In contrast, the use of activated bauxite as a heterogeneous catalyst allowed for easier separation and a higher - quality end product.

Deciding Factors for Choice of Cracking

Environmental Considerations

Thermal cracking tends to release more greenhouse gases and generates more carbon emissions during the process. The higher energy demand leads to a larger environmental footprint unless the energy source itself is renewable (Kralova and Sjöblom) Catalytic cracking, by lowering the required reaction temperature and improving selectivity, catalytic cracking reduces the overall energy consumption and environmental impact. Additionally, some catalysts can be reused multiple times, further decreasing the environmental footprint of the process (Cerón Ferrusca et al.)

Economic Feasibility

The higher energy requirements make thermal cracking less economically viable, particularly when using waste feedstocks like WCO. The cost of maintaining high temperatures over prolonged periods of time is substantial, which could offset the economic benefits of producing biofuel from waste materials (Yaakob et al.) The lower energy requirements and higher product yield make catalytic cracking a more economically feasible option. By improving yield and reducing energy input, it maximizes the economic benefits of biofuel production from WCO (Cerón Ferrusca et al.)

Thermal cracking, while effective in breaking down hydrocarbons, is less energy - efficient, produces more byproducts, and has a higher environmental impact compared to catalytic cracking. The controlled environment of catalytic cracking allows for higher yield, better energy density, and lower energy input, making it a superior method for biofuel production from WCO. Catalytic cracking aligns better with the goals of optimizing energy density and yield while maintaining sustainability.

In the attached table, the values clearly demonstrate the comparative efficiency of **catalytic cracking** versus **thermal cracking** in biodiesel production. Catalytic cracking offers several key advantages over thermal cracking, which justifies its selection for maximizing yield, minimizing environmental impact, and optimizing energy density.

Maximising Yield

The ester content for catalytic cracking is 96.5%, significantly higher than the 92.5% achieved through thermal cracking. This is crucial for maximizing biodiesel production, as the higher ester content indicates a more complete conversion of triglycerides into biodiesel. Moreover, The levels of free glycerol and total glycerol are lower in catalytic cracking (0.02% and 0.25%, respectively), compared to thermal cracking (0.05% and 0.35%), suggesting that catalytic cracking ensures more complete reactions with fewer byproducts, further enhancing yield.

Minimizing Environmental Impact

Sulfur content is notably lower with catalytic cracking at 10 mg/kg, as opposed to 15 mg/kg for thermal cracking. The reduction in sulfur content has a significant environmental impact, particularly in mitigating acid rain and air pollution. Acid rain occurs when sulfur dioxide (SO_2) and nitrogen oxides (NO_x) are released into the atmosphere, react with water vapor, oxygen, and other chemicals, and form acidic compounds such as sulfuric acid (H_2SO_4) and nitric acid (HNO_3) (US EPA, 2016). These acids then precipitate to the Earth's surface, damaging ecosystems by acidifying soil and water bodies, which disrupts plant and aquatic life. Additionally, acid rain can corrode infrastructure, including buildings and bridges, and harm human health by contributing to respiratory issues. Lower sulfur emissions from catalytic cracking play a vital role in reducing the formation of SO_2, thereby lessening the environmental and health risks associated with acid rain. The higher total contamination in thermal cracking (30 mg/kg versus 24 mg/kg in catalytic) leads to more impurities in the biodiesel, which negatively affects its combustion and contributes to higher emissions of particulates and pollutants. In this context, a Class 1 rating indicates minimal corrosivity, suggesting that fuels produced via catalytic cracking are less likely to cause damage to engines and infrastructure. In contrast, a Class 2 rating denotes higher corrosivity, which can be associated with fuels produced through thermal cracking, potentially leading to greater harm to engine components and infrastructure. (ASTM D130, 2019)

Optimizing Energy Density

The cetane number, which measures combustion quality, is higher for catalytic cracking (54) compared to thermal cracking (47). A higher cetane number ensures better ignition quality, resulting in more efficient energy release during combustion, which contributes to a higher energy density in the fuel. Furthermore, lower viscosity in catalytic cracking (4.3 mm^2/s) compared to thermal cracking (5.4 mm^2/s) ensures smoother flow and more efficient fuel combustion, further contributing to optimized energy density.

In conclusion, catalytic cracking is clearly superior for biodiesel production when prioritizing maximum yield, minimal environmental impact, and optimal energy density. The process's ability to produce a higher ester content, minimize byproducts, and enhance combustion quality makes it the preferred method for sustainable and efficient biofuel production from waste cooking oil.

Deciding Factors for Choice of Catalyst

Product Yield and Purity

Using Heterogeneous Catalysts often leads to higher yields of biodiesel with fewer byproducts, as the solid catalyst can control the reaction pathways more effectively. This minimizes side reactions and increases the proportion of valuable fuel fractions (e. g., alkanes and alkenes) that contribute to the energy density and overall quality of the biofuel. The solid catalyst's surface provides sites for adsorption and reaction, allowing for higher conversion efficiency (Li et al.). In comparison, Homogeneous Catalysts can also deliver high yields but are prone to producing unwanted byproducts, especially when the feedstock has high FFA content. Sodium hydroxide, for instance, can cause soap formation, which decreases biodiesel purity and requires additional steps for purification (Kralova and Sjöblom). This reduces the efficiency of the process and lowers the quality of the final biodiesel product (Yaakob et al.)

Economic Feasibility

Heterogeneous Catalysts tend to have higher upfront costs due to the need for specialized materials like activated bauxite, but their recyclability over multiple cycles makes them more economically feasible in the long term. The ability to reuse these catalysts reduces operating costs and contributes to the overall sustainability of the process (Foteinis et al.) . In contrast, Homogeneous Catalysts are cheaper initially but must be replenished after each cycle, increasing the overall cost due to the need for frequent catalyst replacement and waste management. The liquid nature of NaOH or KOH also increases the complexity of post - reaction purification, which adds to the cost of production (Kralova and Sjöblom) .

Environmental Considerations

Heterogeneous Catalysts have a lower environmental impact due to their ability to be separated, recovered, and reused multiple times, which decreases the need for fresh catalyst materials and reduces waste (Cerón Ferrusca et al.). This results in a cleaner process with less chemical waste that requires disposal. On the other hand, Homogeneous Catalysts create significant amounts of liquid waste, including soaps and unreacted alkali, which must be neutralized and treated before disposal to avoid environmental harm. The presence of sodium or potassium in the final product can also lead to increased water contamination risk during biodiesel washing (Foteinis et al.)

Overall, Heterogeneous Catalysts like activated bauxite are more suitable for achieving high yields and energy efficiency with lower environmental impact. Their recyclability and precise control over reactions make them a more sustainable and economically feasible option for biodiesel production from WCO. Homogeneous Catalysts, while cheaper and faster in reaction, have limitations due to their lower selectivity, higher risk of byproduct formation, and greater environmental impact. Thus, heterogeneous catalysis aligns better with the goals of optimizing yield, fuel purity, and sustainability, while minimizing the environmental and economic costs associated with biofuel production.

7. Comparison with Literature

When compared to the energy density data from Layton (2008), which reported oil energy densities in the range of 35 - 45 GJ/m³, the biodiesel produced in this study achieved an energy density of 32.05 GJ/m³. This slightly lower energy density can be attributed to several factors. First, biodiesel often has a lower energy density than fossil fuels due to its higher oxygen content, which reduces the amount of combustible hydrocarbons per unit volume. Additionally, processing methods, the type of feedstock used, and the presence of impurities can also influence energy density. Based on existing literature, the oxygenation of biodiesel, while contributing to its lower energy density, enhances its combustion efficiency and reduces emissions, including greenhouse gases and sulfur oxides (Layton, 2008). These environmental benefits make biodiesel a compelling alternative to conventional fuels despite the energy density trade - off. The findings underscore the potential of biodiesel to bridge the gap between sustainability and energy needs.

This study has successfully demonstrated that catalytic cracking using activated bauxite is an effective method for optimizing the energy density and yield of biodiesel derived from waste cooking oil. The energy density of **32.05 GJ/m³**, though marginally lower than that of crude oil, is adequate for various applications and provides substantial environmental benefits. By refining the catalytic cracking process and employing environmentally friendly techniques, the production of biodiesel from WCO could contribute significantly to sustainable energy solutions and reduce the global reliance on fossil fuels.

8. Conclusion

This study has demonstrated the effectiveness of catalytic cracking using activated bauxite for optimizing the production of biodiesel from waste cooking oil (WCO). By systematically analyzing the impact of catalysts and reaction temperatures on biodiesel yield and energy density, the research achieved an energy density of 32.05 GJ/m³. While slightly lower than the energy density of petroleum - based fuels, this value is sufficient for a range of practical applications and aligns with the goals of reducing greenhouse gas emissions and enhancing sustainability. Additionally, the lower sulfur content and improved combustion properties of the biodiesel underscore its potential as an environmentally friendly alternative to conventional fuels.

The study also highlighted the advantages of heterogeneous catalysts, such as activated bauxite, which enable more efficient and selective reactions while minimizing byproducts. This not only improves fuel quality and yield but also reduces the environmental footprint of the biodiesel production process. In contrast, homogeneous catalysts, though effective, are associated with higher contamination risks and environmental challenges. The findings emphasize the importance of employing sustainable practices in biofuel production to balance economic feasibility, environmental conservation, and fuel performance.

The community impact of this research is significant. By utilizing WCO as a feedstock, the study contributes to waste reduction and demonstrates the potential for recycling waste materials into valuable energy sources. This aligns with the principles of a circular economy, addressing global waste management challenges while promoting renewable energy solutions. Additionally, the research underscores the importance of localized, scalable biodiesel production in regions like Saudi Arabia, where the availability of WCO and existing industrial infrastructure can support sustainable energy transitions.

Beyond the laboratory, the implications of this study extend to the global community. The results advocate for wider adoption of biodiesel as part of a comprehensive approach to addressing climate change and reducing reliance on fossil fuels. By advancing knowledge in the field of biofuel production and showcasing the viability of sustainable practices, this research provides a framework for future innovations and collaborations aimed at achieving energy security and environmental resilience.

In conclusion, this work contributes to the growing body of knowledge on biodiesel production and its role in sustainable energy systems. By demonstrating the practical, environmental, and economic benefits of catalytic cracking with activated bauxite, the study offers actionable insights that can drive progress toward a cleaner, more sustainable future for communities worldwide.

Supplemental Information

Table 4: Supplemental Information for Raw Data

Term	General Definition
Ester Content	The percentage of esters (compounds formed from the reaction between an acid and an alcohol) present in the final biodiesel product, indicating purity.
Viscosity	A measure of a fluid's resistance to flow. Higher viscosity means the liquid flows more slowly, affecting fuel performance and engine efficiency.
Total Contamination	The level of impurities or contaminants present in the biodiesel, which can affect the fuel's performance and quality.
Cetane Number	A measure of the combustion quality of diesel fuel during compression ignition. A higher number indicates better ignition and combustion properties

Copper Band Erosion Rating	A classification that rates the extent to which a material erodes copper in a test, with lower classes indicating less corrosion risk.
Corrosion	The degradation of materials (usually metals) due to chemical reactions, often accelerated by certain catalysts, affecting the longevity of equipment.
Catalyst Recovery	The ability to recover and reuse the catalyst after the reaction, affecting the overall cost - effectiveness and sustainability of the process.
Water Content	The amount of water present in the biodiesel, usually measured in mg/kg. High water content can lead to microbial growth and affect fuel stability.

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