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Catalytic Performance of Sodium Carbonate as a Heterogeneous Catalyst for Biodiesel Synthesis from Low-Quality Feedstocks

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Research Article

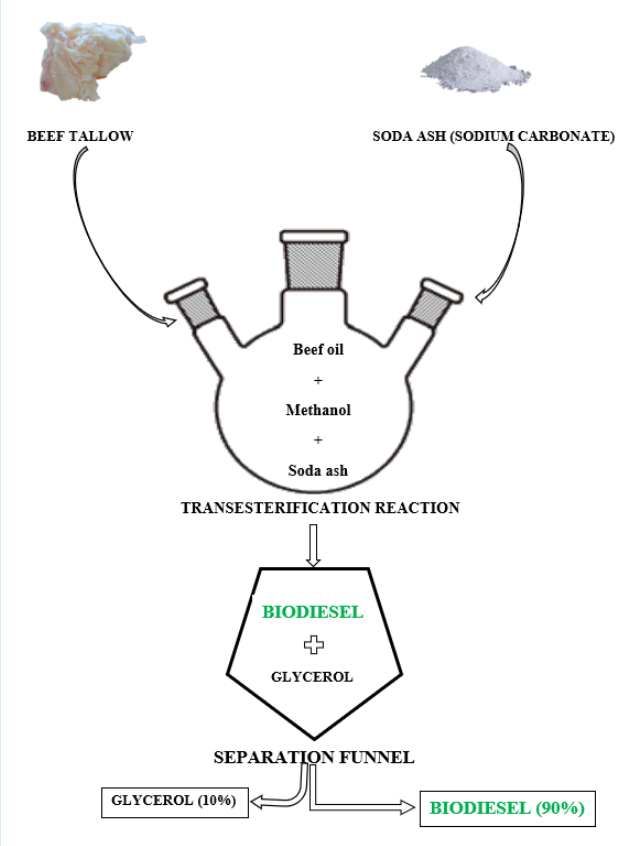
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Abstract



Graphical Abstract

This study investigated the catalytic performance of sodium carbonate (soda ash) as a heterogeneous catalyst in the production of biodiesel from low-quality feedstocks such as waste cooking oil and beef tallow. The focus was placed on its environmental advantages, cost efficiency, and overall effectiveness in operation. To support this, a series of experiments were carried out to identify the optimal reaction conditions (reaction time = 180 min, molar ratio = 1:6, temp = 65°C) needed to maximize biodiesel yield. Additionally, the mechanistic insights into the transesterification process catalyzed by soda ash are discussed, along with recent advancements and challenges in its application. The findings revealed that soda ash has high purity and catalytic potential, achieving an optimal biodiesel yield of nearly 99% at 30 g catalyst loading. The catalyst showed good reusability, maintaining over 96% yield after three cycles, and FTIR analysis confirmed the presence of carbonate functional groups, which has a role as active sites. The produced biodiesel met most ASTM and EN standards, particularly for cetane number, density, acid value, although viscosity deviated from international limits. These results confirm sodium carbonate as a promising, low-cost, and sustainable catalyst, with further optimization required to meet global biodiesel quality standards.

Keywords: Beef Tallow; Biodiesel; Heterogeneous Catalysis; Soda Ash; Transesterification; Sustainability

Abbreviations

FAME: Fatty Acid Methyl Esters; FFA: Free Fatty Acids; ASTM: American Society for Testing and Materials; EN: European Norm; XRF: X-ray Fluorescence Spectroscopy; FTIR: Fourier Transform Infrared; UCO: Used Cooking Oil; WCO: Waste Cooking Oil; PSD: The Particle Size Distribution; HHV: The Higher Heating Value

Introduction

Biodiesel has gained attention as a cleaner and more sustainable alternative to petroleum-based diesel, largely due to its lower greenhouse gas emissions and its ability to biodegrade more readily than conventional fuels. It is typically produced through transesterification, where triglycerides react with an alcohol most commonly methanol in the presence of a catalyst to produce FAME as the main biodiesel product, with glycerol formed as a byproduct [1,2]. In most conventional processes, homogeneous catalysts such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) are used because of their high efficiency. However, these catalysts come with several challenges, including soap formation, difficulties in recovering the catalyst after the reaction, and the generation of large volumes of wastewater [3]. These limitations ultimately contribute to higher overall production costs. Heterogeneous catalysts, which can be easily separated from the reaction mixture and reused, have gained significant attention in biodiesel synthesis. Solid base catalysts, such as alkali and alkaline earth metal oxides (e.g., MgO, CaO) have demonstrated promising catalytic activity with minimal environmental impact [4]. Among these, sodium carbonate (Na_2CO_3) presents an interesting potential as a heterogeneous catalyst due to its natural abundance, low cost, mild basicity, and environmental friendliness. Prior studies indicate that Na_2CO_3 can act as a solid base catalyst for various organic transformations, though its application in biodiesel production remains underexplored [5].

The increasing cost of refined vegetable oils, which constitute the primary feedstock for biodiesel, has driven interest in low-quality and waste-based oils, such as used cooking oil (UCO) and beef tallow. These feedstocks offer a cost-effective and sustainable alternative but introduce additional challenges due to high FFA content and impurities, which lead to catalyst deactivation and formation of soap in traditional homogeneous catalysis [6]. Therefore, the development of a robust, cost-effective, and environmentally friendly heterogeneous catalyst is critical for improving biodiesel production efficiency and sustainability.

This study aimed to assess whether sodium carbonate sourced from local salt producing company Botswana ash mine (BOTASH) can be effectively used as a catalyst for producing biodiesel from low-quality or non-edible feedstocks. It focuses on evaluating how well soda ash performs in the transesterification process, identifying the key reaction conditions that influence biodiesel yield, and determining whether it can serve as a more affordable and sustainable alternative to conventional homogeneous catalysts. Ultimately, the study is significant because it explores ways to lower biodiesel production costs while encouraging the use of locally available resources and underutilized feedstocks. Furthermore, the findings contribute to advancing sustainable energy technologies and support the development of environmentally responsible biofuel production systems, particularly in regions with abundant soda ash resources.

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Reaction Mechanism of Transesterification Using Sodium Carbonate as a Catalyst

Sodium carbonate (Na_2CO_3) functions as a weak heterogeneous base, and its catalytic role begins with the generation of the active nucleophile, methoxide (CH_3O^-). In the presence of methanol, the carbonate ion (CO_3^{2-}) acts as a Brønsted base and abstracts a proton from methanol: $CO_3^{2-} + CH_3OH \rightleftharpoons HCO_3^- + CH_3O^-$

Although this equilibrium is not strongly shifted to the right (due to the moderate basicity of CO_3^{2-}), sufficient methoxide is generated at the catalyst surface to initiate the reaction. The formation of methoxide is the rate-enabling step, as it is the true nucleophile in transesterification.

The methoxide ion then performs a nucleophilic attack on the electrophilic carbonyl carbon of the triglyceride (TG), forming a tetrahedral alkoxide intermediate. This intermediate subsequently collapses, expelling a fatty acid methyl ester (FAME) molecule and generating a diglyceride (DG):

- Nucleophilic attack:
  TG + CH_3O^- → tetrahedral intermediate
- Intermediate breakdown:
  tetrahedral intermediate → FAME + DG^-

The diglyceride anion is then protonated (typically by methanol or bicarbonate), regenerating methoxide or maintaining the catalytic cycle. This sequence repeats for the conversion of diglycerides to monoglycerides (MG), and finally to glycerol (GL), with one FAME molecule produced at each step. The catalytic cycle is sustained through continuous regeneration of methoxide ions, either directly or via equilibria involving bicarbonate (HCO_3^-) and methanol. The heterogeneous nature of Na_2CO_3 also implies that these steps predominantly occur at the solid–liquid interface, where adsorption of methanol and triglycerides enhances local reactant concentration and facilitates proton transfer [7].

The conversion of triglycerides (TG) → diglycerides (DG) → monoglycerides (MG) → biodiesel (FAME) + glycerol [8]

$$Triglyceride + 3CH_3OH \xrightarrow{soda\ ash} 3Biodiesel(FAME) + Glycerol \quad (1)$$

$$Yield\ (\%) = \left(\frac{Weight\ or\ Volume\ of\ Biodiesel\ produced}{Weight\ Volume\ of\ Initial\ Oil\ Used} \right) * 100 \quad (2)$$

Reaction Pathway:
Step 1: Triglyceride + Methanol → Diglyceride + Methyl Ester
Step 2: Diglyceride + Methanol → Monoglyceride + Methyl Ester
Final step: Monoglyceride + Methanol → Glycerol + Methyl Ester [9]
FFA + Na_2CO_3 → Soap (undesired side reaction at high FFA levels)

Comparative Characteristics of Commonly Used Catalysts for Biodiesel Production

A comparative overview of commonly used catalysts for biodiesel synthesis is presented in table 1, highlighting key characteristics such as catalyst type, reusability, sensitivity to free fatty acids (FFA), risk of soap formation, separation ease, and relative cost. The table illustrates that while homogeneous catalysts such as KOH and NaOH are widely used due to their high catalytic activity and low cost, they suffer from major drawbacks including difficulty in separation, lack of reusability, and high sensitivity to FFA, which promotes soap formation. In contrast, heterogeneous catalysts such as CaO, ZnO, and sodium carbonate (Na_2CO_3) offer advantages including catalyst recovery, easier separation, and potential reusability, making them more attractive for sustainable biodiesel production processes [10].

Catalyst	Type	Reusability	Sensitivity to FFA	Soap Formation Risk	Separation Ease	Cost	References
NaOH/KOH	Homogeneous	No	High	High	Difficult	Low	[11,12]
H_2SO_4 (Sulfuric Acid)	Homogeneous	No	Low (used in esterification)	Low	Difficult	Low	[13]
CaO (Calcium Oxide)	Heterogeneous	Yes	Moderate	Low	Easy	Low	[14,15]
ZnO (Zinc Oxide)	Heterogeneous	Yes	Moderate	Low	Easy	Moderate	[16,17]
Na_2CO_3	Heterogeneous	Yes	Moderate	Low	Easy	Low	

Table 1: Comparison of different catalysts for biodiesel production.

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Materials and Methods

The primary materials used in this study include soda ash (Na_2CO_3) from a BOTASH mine as the catalyst, beef tallow from a local beef processing company (BMC) and waste cooking oil C as the feedstock for biodiesel production. Methanol (CH_3OH) of analytical grade (≥99.5% purity) from Rochelle was used as the alcohol in the transesterification reaction. Additional reagents, including potassium hydroxide (KOH) and hydrochloric acid (32% HCl), were used for titration to determine the acid value and the free fatty acid content. Hexane and acetone were used as solvents in sample preparation and purification. Hexane was employed as a non-polar extraction solvent to dissolve and recover lipid fractions from beef tallow and used cooking oil, while acetone was used during purification to remove polar impurities, residual moisture and catalyst contaminants, thereby improving feedstock quality prior to transesterification.

Preparation of Beef Tallow and Waste Cooking Oil

The beef tallow feedstock was pre-treated to remove moisture and volatile impurities before transesterification. It was first heated to 110°C for 60 minutes to eliminate residual water, followed by filtration to remove solid particles and insoluble impurities. The filtered tallow was stored in an airtight container at room temperature before characterization. The soda ash catalyst was dried in an oven at 105°C for 2 hours to remove any absorbed moisture before characterization and catalytic testing. For experiments involving catalyst reusability, the recovered catalyst was washed with methanol, dried and stored for subsequent use.

Waste cooking oil (WCO) was collected from local restaurants and fast-food outlets around Palapye and underwent a pre-treatment process to remove impurities. Initially, the oil was filtered using a Whatman No. 1 filter paper to remove solid residues and food particles. Finally, the pre-treated oil was heated to 110°C for 60 minutes to remove any remaining moisture before being stored in an airtight container for subsequent transesterification.

Characterization of Materials

Soda Ash Characterization

The chemical composition of soda ash was determined using a Niton XL5 Plus Handheld XRF Analyzer, which identified the major and minor elements present. Functional group identification was conducted using an INVENIO FT-IR Spectrometer. The composition of the main active component, sodium carbonate (Na_2CO_3), was determined using titration with an 800 Dosino Titrino titrator, which allows precise quantification of carbonate content. Available sodium (expressed as Na_2O) was also derived from this analysis. Impurities such as sulphates (Na_2SO_4) were measured using 940 Professional IC Vario (Ion chromatography), a method well-suited for detecting dissolved ionic species at low concentrations. Chloride content (NaCl) was analyzed using an 810 Sample Processor 915 KF Ti-Touch titrator, ensuring accurate determination of halide impurities. Water-insoluble matter was measured through filtration and gravimetric analysis, while moisture content (loss on drying at 270 °C) was determined by controlled heating. Organic carbon content was quantified using a CM5017 Carbon coulometer (Model CM5015), which measures carbon levels through coulometric detection. Finally, bulk density was obtained using the pour method, providing insight into the physical handling properties of the soda ash.

Particle Size Distribution

The particle size distribution (PSD) of soda ash was determined using the sieve analysis method in accordance with standard procedures. A representative sample of the catalyst was oven-dried at 105 °C to remove moisture and then carefully weighed before being placed on a stack of sieves arranged in descending order of mesh sizes (2000 µm, 1400 µm, 212 µm, and 75 µm), with a pan at the bottom to collect fines. The sample was subjected to mechanical shaking for 15 minutes using a sieve shaker to ensure proper separation of particles. The retained mass on each sieve was collected, weighed, and expressed as a cumulative percentage by mass (% m/m).

Feedstock Characterization

The physicochemical properties of beef tallow and waste cooking oil were evaluated before its use in biodiesel synthesis. Moisture content was determined using C20S Coulometric KF Titrator, while acid value and free fatty acid (FFA) content were measured using an acid-base titration method with potassium hydroxide (KOH). The FFA content was estimated from the acid value using the relationship below:

$$Acid\ value = \frac{V * N * MW_{KOH}}{W} \qquad (1)$$

$$\%FFA = \frac{V * N * MW_{C18:1}}{W * 1000} \qquad (2)$$

The fatty acid composition was analyzed using HP 6890 GC/5973 MSD gas chromatography-mass spectrometry (GC-MS), and the viscosity and density were measured at 40°C using STANHOPE-SETA KV-6 Viscometer and digital densitometer, respectively. The higher heating value (HHV) of beef tallow was determined using a bomb calorimeter to

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assess its energy content.

Experimental Setup, Procedure, and Product Analysis

Transesterification Reaction and Catalyst Loading Investigation

The transesterification reactions were conducted in a 5000 mL three-necked round-bottom flask equipped with an overhead stirrer, reflux condenser, and thermometer to maintain a controlled reaction environment, as indicated in Figure 1. A measured amount (1000ml) of preheated beef tallow or waste cooking oil was mixed with methanol at a fixed methanol-to-oil molar ratio of 6:1, with sodium carbonate (Na_2CO_3) as the catalyst. Catalyst loading varied between 10 g and 40 g to study its effect on biodiesel yield. The reaction temperature was maintained at 65°C, and the reaction was allowed to proceed for 3 hours under continuous stirring. After the reaction, the mixture was filtered then cooled to room temperature, and the biodiesel and glycerol phases were separated using a separating funnel. A rotary evaporator was used to remove excess methanol.

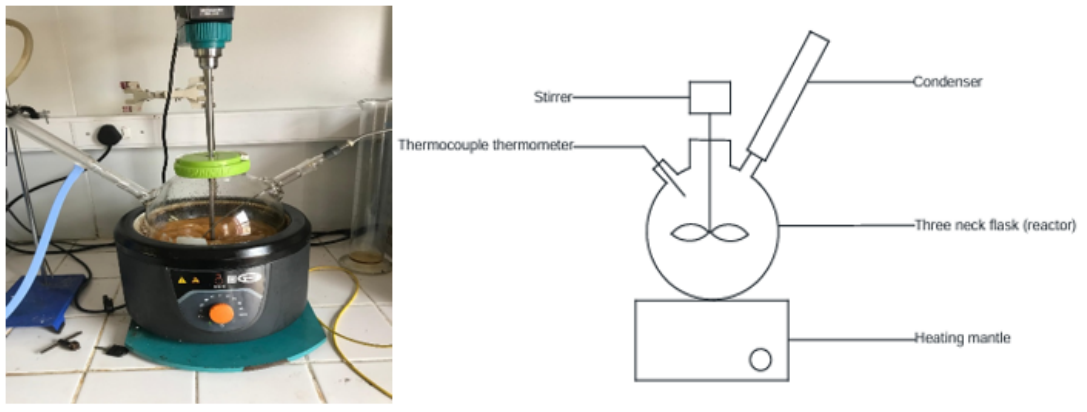


Figure 1: Experimental setup of the transesterification process.

Biodiesel Yield and Product Characterization

The biodiesel yield (%) was calculated based on the initial weight of the feedstock. The produced biodiesel was analyzed for physicochemical properties to ensure compliance with ASTM D6751 and EN 14214 standards [18]. The density and viscosity were measured using a digital viscometer, while the flash point was determined according to ASTM D93. The cetane number was assessed using ASTM D613 [19], and the acid value was determined using ASTM D664. The fatty acid profile was analyzed using GC-MS, and the biodiesel's saponification and iodine values were measured to assess its chemical stability.

Catalyst Recovery and Reusability

The used catalyst was recovered by filtration, washed with methanol and dried at 100°C before being reused. The reusability of the catalyst was assessed over three consecutive reaction cycles, with the biodiesel yield and physicochemical properties analyzed after each cycle. To evaluate the stability of the recovered catalyst, FTIR analyses were performed after each reuse to detect potential structural or compositional changes.

Results and Discussions

Soda Ash Composition

Chemical analysis of soda ash (Na_2CO_3) confirmed a high purity level of 99.51%, which exceeds the minimum specification of (99.2%), as depicted in Table 2. The available sodium oxide (Na_2O) content was 58.28%, again slightly higher than the required minimum of 58.0%, confirming strong catalytic potential. Impurities such as sodium bicarbonate (0.11%), sulphates (1077 ppm), and chlorides (988 ppm) were found in relatively low amounts and within acceptable limits. Importantly, water insolubles (0.08%) and loss by drying (0.39%) were both below specification thresholds, suggesting that the soda ash has low moisture retention and is chemically stable. Bulk density (0.92 g/cm^3) also fell within the acceptable range.

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	Chemical Formula	Equipment Used	Units	Specification	Value
Sodium Carbonate	Na2CO3	Titrino (titration)	%m/m	99.2 (min)	99.5
Available Sodium	Na2O		%m/m	58.0 (min)	58.3
Sodium Bicarbonate	NaHCO3		%m/m		0.11
Sulphates	Na2SO4	Ion chromatography	ppm m/m	2 000 (max)	1077
Chlorides	NaCl	Ti Touch	ppm m/m	1 500 (max)	988
Water Insolubles			%m/m	0.1 (max)	0.08
Loss by Drying	at 270 oC		%m/m	0.5 (max)	0.39
Organic Matter	as C (standard)	Carbon coulometer	ppm m/m	1800 (max)	1464
Bulk density	Pour		g/cc	0.90-1.10 g/cm3	0.92

Table 2: Chemical analyses for soda ash.

Particle Size Distribution

The particle size distribution analysis of soda ash revealed that the majority of particles were within the fine size range, with over 96% retained above 75 µm and only 3.34% passing below 75 µm, which is well within specification limits. This indicates that the soda ash sample is composed predominantly of uniform, moderately fine particles with very little dust content. From a catalytic performance perspective, this distribution is advantageous. Finer particles generally provide a larger surface area-to-volume ratio, which enhances the availability of active sites for the transesterification reaction, thereby improving catalytic efficiency. At the same time, the limited fraction of ultra-fine particles (<75 µm) reduces potential issues of catalyst loss during recovery and minimizes excessive agglomeration that could hinder mixing and mass transfer [20].

The presence of a small proportion of coarser particles (16.66% retained on the 1400 µm sieve) is not detrimental but may slightly reduce the effective surface area compared to uniformly smaller particles. However, this also contributes positively to catalyst handling by improving flow properties and reducing excessive powdering [21]. Overall, the PSD profile suggests that soda ash is well-suited for use as a heterogeneous catalyst, offering a balance between reactivity, stability, and reusability. This balance may partly explain the high biodiesel yields observed at optimized catalyst loading in this study [22,23].

Sieve Size (µm)	Cumulative Retained (% m/m)	Cumulative Passing (% m/m)	Specification Limit
2000	0.65	99.35	Max 1% retained
1400	16.66	83.34	Max 30% retained
212	86.36	13.64	Min 80% retained
75	96.66	3.34	Min 95% retained
<75	100	0	Max 5% passing

Table 3: Particle size distribution of Soda Ash (Na_2CO_3) by Sieve Analysis.

Free Fatty Acid Content and Acid Value

The free fatty acid (FFA) content and acid value of the selected feedstocks was determined to assess their suitability for biodiesel production using sodium carbonate (Na_2CO_3) as a heterogeneous base catalyst. The results in Table 4 show notable differences in FFA levels among the feedstocks analyzed. Used cooking oil samples exhibited relatively low FFA values, with used cooking oil C, used cooking oil A, and used cooking oil B recording FFA contents of 0.012, 0.013, and 0.029 respectively. These values fall well below the operational threshold of 5% FFA (0.05 fraction), indicating that these feedstocks are suitable for base catalyzed transesterification using soda ash, where minimal soap formation is expected.

In contrast, the beef tallow samples showed significantly higher FFA contents. Beef tallow from Palapye recorded the highest value (0.139), followed by Maun (0.087) and BMC (0.043). The Palapye and Maun samples exceed the acceptable limit for soda ash catalysis and would likely promote saponification during the reaction, thereby reducing

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biodiesel yield and complicating product separation. Although the BMC sample falls below the 5% threshold, its relatively higher acidity may still influence catalytic efficiency compared to the cooking oil samples [24]. These findings confirm that sodium carbonate performs effectively with feedstocks containing FFA below 5% (0.05 fraction), while high-FFA feedstocks such as certain beef tallow samples would require pretreatment, such as acid esterification, to reduce FFA levels prior to biodiesel production [25].

Feedstocks	Acid value	Free Fatty Acids (%)
Used Cooking oil C	2.47	1.20
Used Cooking oil B	5.82	2.90
Used Cooking oil A	2.56	1.30
Beef tallow Palapye	21.71	13.90
Beef tallow Maun	13.59	8.70
Beef tallow BMC	8.85	4.30

Table 4: Free Fatty Acid content for used cooking oil and beef tallow.

Effects of Catalyst Loading

The effect of catalyst loading on fatty acid methyl ester (FAME) yield was investigated for both used cooking oil (UCO) and beef tallow from BMC using sodium carbonate (Na_2CO_3) as a heterogeneous catalyst. As shown in the figure 2, biodiesel yield increases with increasing catalyst loading for both feedstocks up to an optimum value, after which a slight decline in yield is observed.

For used cooking oil 1000ml, the FAME yield increased steadily from approximately 96.5% at 10 g catalyst loading to a maximum of about 99% at 30 g. This trend indicates that increasing catalyst loading enhances the availability of active basic sites, thereby accelerating the transesterification reaction and improving triglyceride conversion. Similar observations have been reported in heterogeneous catalysis studies, where increased catalyst concentration improved contact between reactants and catalytic sites, resulting in higher biodiesel yields [26]. Beyond 30 g, however, the yield shows a slight decline, decreasing to about 98.3% at 40 g. This decrease may be attributed to excessive catalyst particles causing mass transfer limitations, increased mixture viscosity, and possible aggregation of catalyst particles, which reduces the effective surface area available for reaction [12].

In comparison, beef tallow consistently produced lower biodiesel yields across all catalyst loadings. The yield increased from approximately 90.5% at 10 g catalyst loading to about 94.5% at 30 g, after which it declined slightly with further catalyst addition. The lower performance of beef tallow relative to used cooking oil can be attributed primarily to its higher FFA content and higher saturation level. Animal fats such as beef tallow typically contain higher levels of saturated fatty acids and impurities compared to waste cooking oils. High FFA content promotes saponification reactions when basic catalysts such as sodium carbonate are used, leading to soap formation that consumes the catalyst and reduces biodiesel yield [27]. Additionally, the higher melting point and viscosity of beef tallow can hinder effective mixing and mass transfer during transesterification, thereby limiting catalyst–reactant interactions [28].

The decline in yield observed for both feedstocks beyond the optimum catalyst loading can also be explained by excessive catalyst concentration promoting mass transfer limitations and side reactions. When the catalyst concentration becomes too high, the reaction mixture may become overly viscous, reducing effective mixing and lowering the contact between methanol and triglycerides. Furthermore, excessive base catalyst can increase soap formation, particularly in feedstocks containing residual free fatty acids, which interferes with phase separation and reduces biodiesel recovery [29].

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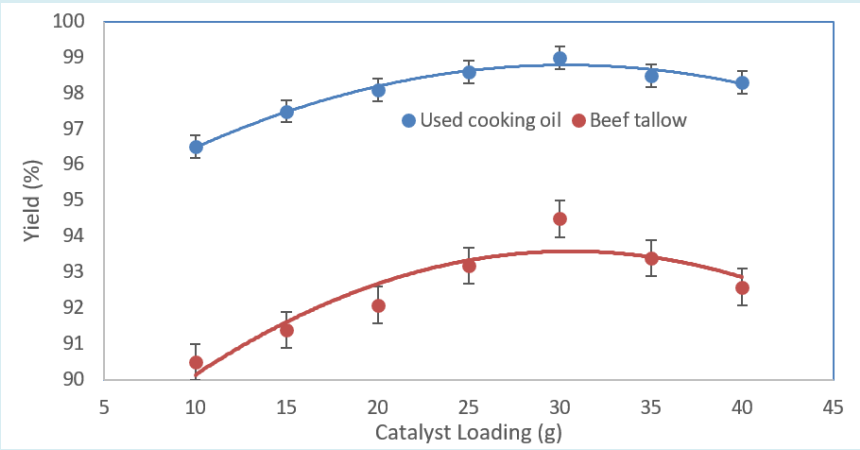


Figure 2: Effect of Na_2CO_3 catalyst loading on biodiesel yield.

Catalyst Reusability Test/Profile

The reusability of the catalyst is a very important feature to consider when determining the catalyst sustainability and for commercial use. Figure 3 shows the result of three reusability studies on the Na_2CO_3 catalyst for biodiesel production from WCO with a very slight decrease (gradual decline) from 99 to 96% after the first three runs. The decline in catalytic performance of the recovered catalyst is likely due to product molecules accumulating on its surface, rather than fresh reactants interacting with it, which can lead to catalyst clogging [30]. In addition, reaction intermediates may occupy and block the catalyst's active sites, preventing effective interaction with the reactants and ultimately reducing its overall activity.

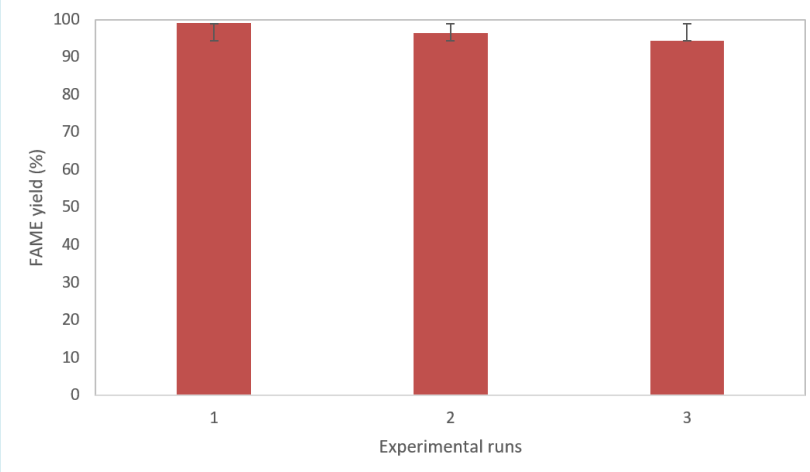


Figure 3: Reusability profile of the Na_2CO_3 catalyst.

FTIR Analysis

The FTIR spectra of dense soda ash (black) and light soda ash (red) reveal characteristic carbonate functional groups, with notable differences in peak intensity and transmittance. A strong absorption peak is observed around 1400–1500 cm^{-1}, corresponding to the asymmetric stretching vibrations of carbonate (CO_3^{2-}) ions, which confirms the presence of sodium carbonate (Na_2CO_3), the primary component of soda ash. The higher intensity of this peak in light soda ash suggests differences in crystallinity or packing density compared to dense soda ash. Additionally, peaks in the 800-1000 cm^{-1} range correspond to C-O bending vibrations in carbonate compounds, with slight variations that may indicate differences in hydration levels or impurities [31].

A broad absorption feature is also present in the 3000-3600 cm^{-1} range, attributed to O-H stretching vibrations, which may be linked to residual moisture in the samples [32]. The relatively low intensity of this peak suggests

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minimal water content in both soda ash types, though light soda ash appears to retain slightly more moisture, possibly due to its higher surface area and porosity. These structural and compositional variations could influence their catalytic performance in biodiesel synthesis, particularly in terms of reactivity, mass transfer efficiency, and recyclability in heterogeneous catalysis [33].

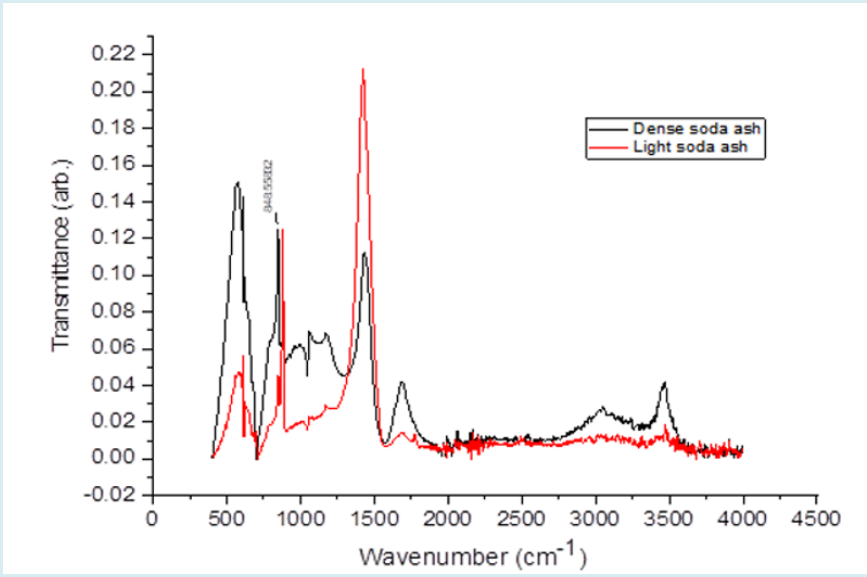


Figure 4: FTIR C-O bending vibrations and O-H stretching vibrations of sodium carbonate.

Physio-chemical Properties of Biodiesel

The physio-chemical properties of the biodiesel produced using sodium carbonate (Na_2CO_3) were evaluated against ASTM D6751 specifications established by ASTM International and EN 14214 standards issued by the European Committee for Standardization as indicated in table 5. The density of the biodiesel (881 kg/m^3) falls within the prescribed range (860-900 kg/m^3) of both standards, indicating effective conversion of triglycerides to fatty acid methyl esters (FAME) and acceptable fuel injection characteristics. The flash point (139°C) significantly exceeds the minimum requirements (≥130°C ASTM; >120°C EN), confirming efficient methanol removal and safe handling properties. However, the kinematic viscosity (7.47 mm^2/s) exceeds both ASTM (1.9-6.0mm^2/s) and EN (3.5-5.0mm^2/s) limits. Elevated viscosity suggests incomplete transesterification or the presence of residual glycerides. This deviation may affect atomization and combustion efficiency indicating that further process optimization is required. The water content (0.047%) complies with ASTM (<0.05%) but exceeds the EN limit (<0.02%), suggesting that additional drying or purification may be necessary to meet the European specifications. The calorific value (38.04 MJ/kg) is slightly lower than that of petroleum diesel 43 MJ/kg, which is typical for biodiesel due to its oxygenated molecular structure [4].

Property	Na_2CO_3 results	ASTM standard	EU standard
Cetane number	52	48-65	>51
Density (kg/m^3)	881	860-900	860-900
Viscosity (mm^2/s)	7.47	1.9-6.0	3.5-5.0
Flash point (°C)	139	≥130	>120
Cloud point (°C)	6	Variable	Variable
Acid value	0.37	<0.5	<0.8
Water content (%)	0.047	<0.05	<0.02
Calorific value (MJ/kg)	38.04	Variable	Variable

Table 5: Physio-chemical properties of biodiesel produced using Na_2CO_3 [18].

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Biodiesel Fatty Acid Profile

The fatty acid methyl ester (FAME) composition of biodiesel produced from beef tallow and used cooking oil was determined using gas chromatography–mass spectrometry (GC-MS). The results presented in Table 6 reveal notable differences in the fatty acid profiles of the two feedstocks, reflecting their distinct lipid compositions. Biodiesel derived from beef tallow was dominated by saturated fatty acids, particularly hexadecanoic acid (palmitic acid), which accounted for 55.4% of the total composition. Other significant components included tetradecanoic acid (myristic acid) (14.2%), 9-octadecenoic acid (oleic acid) (14.2%), and octadecanoic acid (stearic acid) (12.5%), with a minor contribution from 9-hexadecenoic acid (3.4%). The predominance of saturated fatty acids is characteristic of animal fats and contributes to higher cetane numbers and improved oxidative stability of the resulting biodiesel. However, high saturation levels can negatively affect cold-flow properties, leading to higher cloud and pour points [34,35].

In contrast, biodiesel produced from used cooking oil exhibited a higher proportion of unsaturated fatty acids. The major components were oleic acid (40.8%) and linoleic acid (34.8%), followed by palmitic acid (14.6%) and stearic acid (7.4%), with minor fractions of 11-hexadecenoic acid (0.9%) and 10-octadecenoic acid (1.3%). The higher degree of unsaturation observed in used cooking oil biodiesel is typical of vegetable oil-derived feedstocks and generally contributes to improved cold-flow properties and lower viscosity compared to biodiesel derived from animal fats [36]. The observed variations in fatty acid composition significantly influenced the physicochemical properties of biodiesel fuels. Biodiesel made from feedstocks high in saturated fatty acids, such as beef tallow, generally shows better resistance to oxidation and improved ignition properties. In contrast, biodiesel derived from more unsaturated sources like used cooking oil tends to perform better at lower temperatures due to its superior cold-flow behavior. These differences underline how critical the choice of feedstock is in shaping the overall quality and performance of biodiesel fuel [37-39].

Fatty Acid	Formula	Fractional Composition (%)	
		Beef Tallow	Used Cooking Oil
Hexadecanoic acid (Palmitic acid)	$C_{17}H_{34}O_2$	55.48	14.6
Tetradecanoic aid (myristic acid)	$C_{15}H_{30}O_2$	14.26	-
9-Octadecenoic acid (Oleic acid)	$C_{19}H_{36}O_2$	14.25	40.82
Octadecanoic acid (Stearic acid)	$C_{19}H_{38}O_2$	12.55	7.45
14,17-Octadecadienoic acid (Linoleic acid)	$C_{19}H_{34}O_2$	-	34.82
9-Hexadecenoic acid	$C_{17}H_{32}O_2$	3.46	-
11-Hexadecenoic acid	$C_{17}H_{32}O_2$	-	0.93
10-Octadecenoic acid	$C_{19}H_{36}O_2$	-	1.39

Table 6: Fatty acid profile of biodiesel derived from beef tallow and used cooking oil.

Integrated Discussion of Results

The results of this study collectively demonstrate that sodium carbonate (Na_2CO_3) is a promising low-cost heterogeneous catalyst for biodiesel production from low-quality feedstocks. The high purity of the soda ash (99.51%), together with its low moisture and impurity content, contributed significantly to its catalytic effectiveness by providing sufficient carbonate active sites for methoxide formation during transesterification. FTIR analysis further confirmed the presence of carbonate functional groups responsible for the catalyst's basic behavior, while the low O–H absorption bands indicated minimal moisture content, which is important for reducing soap formation and hydrolysis reactions.

The particle size distribution also played an important role in catalyst performance. The predominance of moderately fine particles provided adequate surface area for catalyst–reactant interaction while still allowing easier catalyst recovery and reuse. This partly explains the high biodiesel yields achieved, and the catalyst stability observed during the reusability study, where yields remained above 96% after three cycles. The slight decline in activity was likely caused by blockage of active sites by reaction intermediates and residual products.

Feedstock quality strongly influenced biodiesel yield and overall process efficiency. Used cooking oil, which contained low FFA levels (1.2–2.9%), produced significantly higher biodiesel yields than beef tallow. In contrast, beef tallow

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samples with high FFA content promoted saponification reactions, resulting in soap formation, catalyst consumption, and lower biodiesel recovery. These findings confirm that Na_2CO_3 performs best with low-FFA feedstocks, while high-FFA oils require pretreatment before transesterification.

Catalyst loading experiments showed that biodiesel yield increased with increasing catalyst amount up to an optimum loading of 30 g, where the highest yield (~99%) was achieved for used cooking oil. Increased catalyst loading improved the availability of active basic sites and enhanced triglyceride conversion. However, further increases beyond 30 g slightly reduced yield due to mass transfer limitations, increased mixture viscosity, and catalyst agglomeration. Beef tallow consistently produced lower yields because of its higher saturation level, viscosity, and acidity, which limited efficient catalyst–reactant interaction.

The physicochemical properties of the biodiesel produced met most ASTM D6751 and EN 14214 standards, particularly for density, cetane number, flash point, and acid value, confirming successful conversion to fatty acid methyl esters (FAME). However, viscosity exceeded standard limits, likely due to incomplete transesterification and the presence of residual glycerides, especially in biodiesel derived from beef tallow. GC–MS analysis supported these findings by showing that beef tallow biodiesel contained higher levels of saturated fatty acids, which improved cetane number and oxidative stability but negatively affected flow properties. In contrast, used cooking oil biodiesel contained more unsaturated fatty acids, resulting in better cold-flow behavior and lower viscosity.

Challenges and Limitations of Sodium Carbonate Catalyst

Despite the promising catalytic performance of sodium carbonate (Na_2CO_3), several limitations were observed during this study that directly influenced biodiesel yield and fuel quality. One major challenge was the sensitivity of the catalyst to high free fatty acid (FFA) content in the feedstock. Beef tallow samples with high FFA levels, particularly those from Maun (13.9%) and Lobatse (8.70%), produced lower biodiesel yields compared to waste cooking oil. This reduction in performance is attributed to saponification reactions between FFAs and the basic Na_2CO_3 catalyst, which consumed active catalytic species, promoted soap formation, and complicated biodiesel–glycerol phase separation. These observations confirm that Na_2CO_3 performs more effectively with low-FFA feedstocks or pretreated oils.

Another limitation observed was the relatively high catalyst loading required to achieve maximum biodiesel yield. Optimal conversion was only attained at 30 g catalyst loading, indicating that the mild basicity of Na_2CO_3 provides lower catalytic activity compared to stronger homogeneous bases such as NaOH and KOH. Beyond the optimum loading, biodiesel yield declined slightly for both feedstocks, likely due to increased mixture viscosity, catalyst agglomeration, and mass transfer limitations that reduced effective contact between reactants and catalytic active sites.

The physicochemical characterization of the biodiesel also revealed limitations associated with the catalyst system. Although most ASTM D6751 and EN 14214 fuel specifications were satisfied, the viscosity of the produced biodiesel (7.47 mm^2/s) exceeded the recommended international limits. This suggests incomplete transesterification or the presence of residual glycerides, which may be linked to the comparatively weak basic strength of Na_2CO_3 and slower reaction kinetics. Additionally, the water content slightly exceeded the EN 14214 requirement, highlighting the sensitivity of the catalyst to moisture and the need for improved drying and purification steps. These findings indicate that while sodium carbonate is a promising low-cost and reusable heterogeneous catalyst, further optimization of pretreatment methods, catalyst modification, and reaction conditions is necessary to improve catalytic efficiency and biodiesel quality, particularly for high-FFA feedstocks.

Conclusion

This study demonstrated the feasibility of using locally sourced sodium carbonate (Na_2CO_3) as a low-cost heterogeneous catalyst for biodiesel production from low-quality feedstocks, namely waste cooking oil and beef tallow. The suitability of the feedstocks was strongly influenced by their FFA content. Waste cooking oil samples contained relatively low FFA levels (1.2–2.9%), making them suitable for direct base-catalyzed transesterification. In contrast, beef tallow samples exhibited significantly higher FFA contents (4.3–13.9%), which increased the likelihood of soap formation and reduced biodiesel yield. To minimize catalyst deactivation and ensure efficient transesterification, the feedstocks underwent pretreatment processes including filtration, heating, and moisture removal prior to reaction. The highest biodiesel yield (~99%) was obtained from waste cooking oil at an optimum catalyst loading of 30 g, while lower yields were observed for beef tallow due to its higher acidity and saturation level.

The catalytic activity of Na_2CO_3 was attributed to its ability to generate methoxide ions in situ, facilitating triglyceride conversion at the solid–liquid interface. The catalyst also demonstrated good reusability, maintaining yields above 96% after three consecutive cycles. GC–MS analysis confirmed the formation of fatty acid methyl esters (FAME), verifying successful biodiesel synthesis. The FAME

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profile showed that biodiesel derived from beef tallow was rich in saturated fatty acids, particularly palmitic acid, whereas biodiesel from used cooking oil contained higher proportions of unsaturated fatty acids such as oleic and linoleic acids. These compositional differences significantly influenced the fuel properties of the resulting biodiesel. Furthermore, the produced biodiesel complied with most ASTM D6751 and EN 14214 requirements, although viscosity and water content require further optimization. Overall, sodium carbonate shows strong potential as an environmentally friendly and sustainable heterogeneous catalyst for biodiesel production from low-cost feedstocks.

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