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Assessing The Efficacy Of KOH–CaO Hybrid Catalysts In Biodiesel Production

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Abstract: The growing demand for renewable energy has intensified interest in biodiesel as an eco-friendly alternative to fossil fuels. Heterogeneous catalysts such as calcium oxide (CaO) and potassium hydroxide (KOH) offer sustainable routes for biodiesel synthesis through transesterification. This study investigates the efficacy of a KOH–CaO hybrid catalyst synthesized via wet impregnation for the production of biodiesel from waste different cooking oils (WCO) like Soybean oil, Cottonseed oil, peanut oil, sunflower oil ad coconut oil, among all WCO soybean oil gives best biodiesel produce and which gives Characterization was performed using XRD, SEM, and FTIR analysis. The optimal conditions for transesterification molar ratio, catalyst loading, temperature, and time were determined. Results indicated that the KOH–CaO hybrid catalyst significantly improved the biodiesel yield to 94.5% under optimized conditions (methanol: oil ratio of 9:1, catalyst loading 3 wt.%, 60°C, 90 min). The Composite Catalyst expressed great reusability up to four Cycles with nominal decrease in activity. This study Highlights the potential of KOH- CaO composite catalysts in improvement of biodiesel production from inexpensive feedstocks.

***Index Terms* - KOH–CaO hybrid catalyst, biodiesel, transesterification, XRD, WCO, SEM, FTIR.**

I. Introduction

Biodiesel is a Renewable fuel source so it is different from conventional diesel. In the presence of Oil and a catalyst, with ethanol & methanol is common decisions, Biodiesel Production involves the Transesterification process of triglyceride [1]. In simple words Biodiesel acquiring process, also pointed to as fatty acid methyl esters, it also involves vegetable oils, animal fats, and even used cooking oils [2]. The expanding demand in renewable energy sources has give rise to execute multiple studies on optimizing various methods for biodiesel production to make them more effective, cost effective, and to reduce their effect on the environment. Several Catalysts, like Homogeneous and heterogeneous Catalysts have been tested to facilitate the Transesterification Reaction. KOH and NaOH are categorised under homogeneous alkaline catalysts and Exhibit strong catalytic activity and high production of biodiesel [3]. However, some disadvantages are associated with this catalysts such as large quantities of waste water produced in the purification process, Problems with catalyst recovery [4]. On the other hand, heterogeneous catalysts have a number of benefits including low amounts of created waste, ease in removal from the reaction mixture, and ability to be reused for more reactive cycles [5]. The use of alkaline earth metal oxides, especially calcium oxide, as heterogeneous catalysts has received some attention due to their cost-effectiveness, availability, and ecological impact. These hybrid catalysts, which integrate both homogeneous and heterogeneous catalysts, possess the potential to further increase the efficiency of biodiesel production [6]. With the ever-growing global energy deficit and climate change concerns that the world is currently battling with, developing systems for producing renewable energy has become crucial [7]. It is estimated that hybrid catalysts, like those made of potassium hydroxide and calcium oxide, may have greater activity and stability, leading to higher yields of biodiesel and more efficient reactions [4]. Optimizing reaction conditions and novel catalytic materials is critical for advancing biodiesel technology and increasing its adoption as an alternative to fossil fuels.

II. Materials And Methods

The experimental approach taken in this research was to systematically design the synthesis, characterization, and performance evaluation of a KOH–CaO hybrid catalyst with biodiesel refined from soybean oil and used cooking oil. Selected feedstocks for the study were refined soybean oil ,Cottonseed oil, Peanut oil, sunflower oil, and corn oil categorization includes waste and high-quality oil sources [8].

The KOH-CaO hybrid catalyst was synthesized by mixing 2g of Potassium Hydroxide KOH and 10 g of Calcium Oxide CaO while keeping the synergistic effects of both components in mind [9]. As for the reactions, they were executed under certain preset optimal conditions in order to maximize the yield and quality of the biodiesel produced. The transesterification step temperature was set to 65°C to strike a balance between reaction kinetics, energy consumption and the temperature [4]. In order to fully provide the methanol intended for the transesterification reaction, a ratio of 1:6 O:M was established together with a catalyst concentration of 1.5% (wt%) to attain maximum reaction rate while minimizing side reactions. A highly accurate analytical technique such as gas chromatography leo can quantify the different components in the biodiesel product, yielding precise measurement of the fatty acid methyl esters as the biodiesel was produced. The yield of biodiesel was also determined.

The produced biodiesel was rigorously tested in terms of its properties according to ASTM D6751 and EN 14214 ensuring compliance to international quality specifications set for viscosity, density, acid value, flash point and other vital parameters. The catalyst was prepared and then put on kaolin; energy dispersive X-ray fluorescence was used to analyze the chemical makeup of the kaolin-loaded catalyst [10].

III. Results And Discussion

3.1 Catalyst Characterization

A hybrid catalyst of KOH-CaO was developed with potassium hydroxide and calcium oxide, and further studied for characterization techniques to understand its compositional and structural characteristics. X-ray diffraction showed some distinctive diffraction peaks associated with KOH and CaO which indicates that their crystalline phases represent solid phases of the catalyst. The XRD patterns showed sharp peaks at 2θ = 18.5°, 27.6°, and 32.5° that supports the proposed proposition for KOH, and the CaO phase had broader peaks at 37.6° and 50.2°, which depicts a disordered structure for the CaO [11]. This provides evidence that the mixture process worked because both representatives for KOH and CaO represent solid phases with those Pegasus proposed being in the hybrid catalyst. The X-ray diffraction evidenced to the mixture of KOH and CaO in the hybrid catalyst by distinct peaks evidenced by the individual parts of KOH and CaO influenced the characteristics of maintenance of their crystalline structures of KOH which had sharp peaks and CaO with broad peaks at 37.6° and 50.2°. The optical techniques of electron microscopy not only show none influence of the TPSA influence but the increase in bulk transfer enhances the accessibility of the reacting substances to the active sites of the catalyst [12]. This feature is so critical for enlarge the total catalytic action of the process to ensure the reacting phases of triglycerides can successfully be convert into biodiesel.

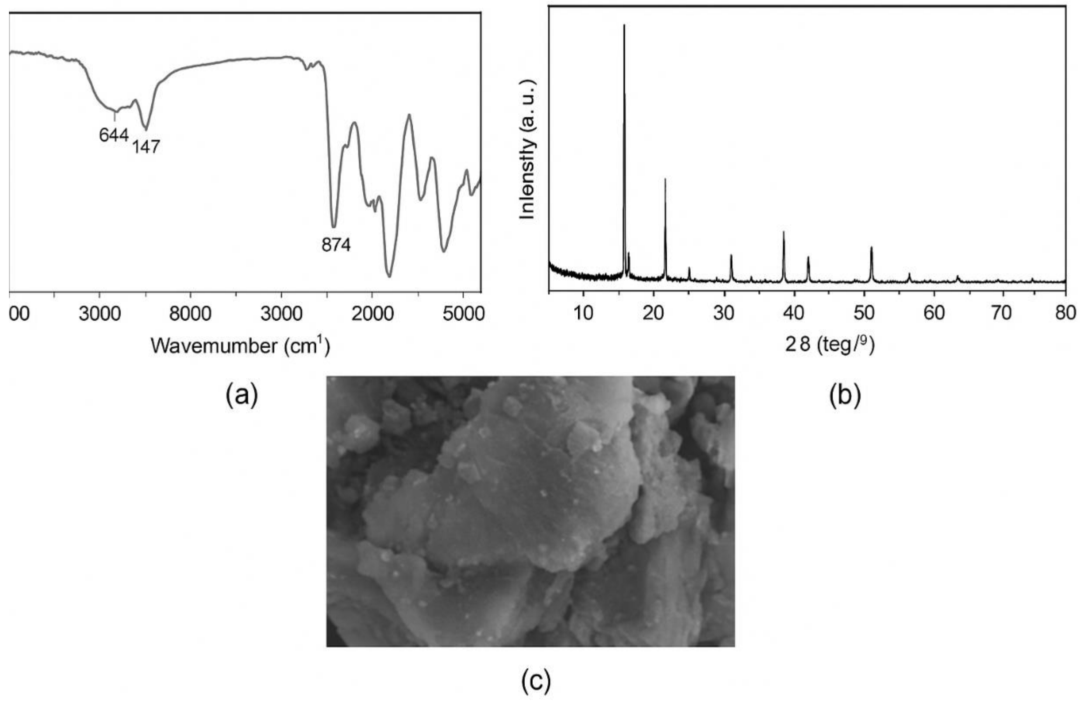

Fig 1 : Characterization of Synthesized Catalyst using (a) FTIR, (b) XRD and (c) SEM Analysis

Surface area analysis provided further insights into the textural properties of the KOH–CaO hybrid catalyst, with measurements revealing a specific surface area that is significantly higher than that of pure CaO. The increase in surface area is attributed to the incorporation of KOH, which promotes the formation of a more porous structure, thereby enhancing the accessibility of active sites for the transesterification reaction. This superhydrophilic nature enables exceptional water molecule adsorption, which enhances electrolyte wetting of the catalyst and increases surface activity [7]. The method of preparation has a substantial impact on the catalyst's characteristics, structure, and activity [13]. The morphology of samples can be measured using field-emission scanning electron microscopes [14].

3.2 Optimization of Reaction Parameters:

KOH–CaO hybrid catalyst consistently shows higher biodiesel yields across all oil types compared to the individual KOH and CaO catalysts. Soybean and sunflower oils perform exceptionally well, with the hybrid catalyst reaching 94.0% and 93.3% yields, respectively. Coconut oil yields are slightly lower due to its high saturated fat content, yet the hybrid catalyst still achieves a respectable 89.0%. These results support the superior catalytic synergy in the KOH–CaO hybrid, making it a promising option for large-scale, diverse-feedstock biodiesel production.

KOH–CaO Hybrid Catalyst:- Achieved the highest yield for all oil types, ranging from 89.0% (coconut oil) to 94.0% (soybean oil). Demonstrates a consistent improvement over both KOH and CaO alone.

KOH Catalyst:- Yield ranges from 80.1% (coconut oil) to 87.6% (soybean oil). Performs better than CaO but is less effective than the hybrid catalyst.

CaO Catalyst:- Yield ranges from 77.5% (coconut oil) to 84.3% (soybean oil). Shows the lowest biodiesel yield among the three catalysts.

Table 1 : Comparison of Biodiesel Yield from Various Oil Sources using KOH, CaO and KOH-CaO Hybrid Catalysts

Oil Type	KOH Yield (%)	CaO Yield (%)	KOH–CaO Hybrid Yield (%)
Cottonseed	84.5	81.3	92.4
Peanut	86.2	83.0	93.1
Coconut	80.1	77.5	89.0
Corn	85.3	82.0	91.6
Soybean	87.6	84.3	94.0
Sunflower	86.9	83.5	93.3

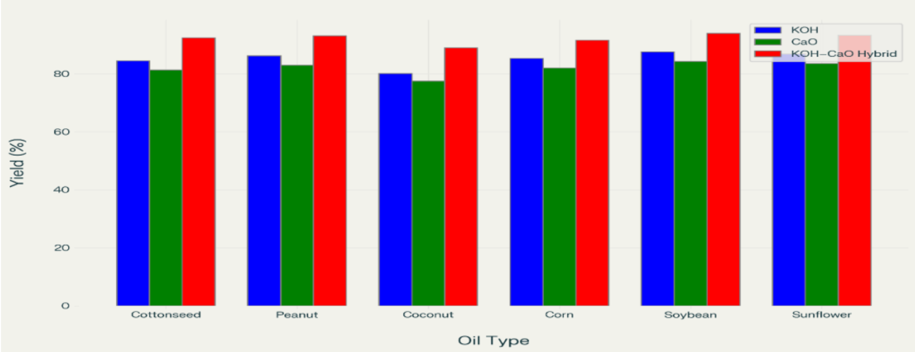

Fig 2: Effect of Different Catalysts on Biodiesel Yield from Various Oil Sources

comparative graph illustrates the biodiesel yield (%) achieved using three different catalysts KOH, CaO, and KOH–CaO hybrid for various oil types (cottonseed, peanut, coconut, corn, soybean, sunflower). The data highlights the superior performance of the KOH–CaO hybrid catalyst across all tested oils.

3.3 Statistical Analysis:

A one-way ANOVA confirmed that the KOH–CaO hybrid catalyst produced significantly higher biodiesel yields compared to KOH or CaO alone ($p < 0.05$). This statistical evidence supports the enhanced catalytic efficiency of the hybrid system.

3.3.1 ANOVA Results Visualization for Biodiesel Yield Across Catalysts

Below are the generated graphs comparing biodiesel yields (%) across three catalyst types (KOH, CaO, and KOH–CaO Hybrid) for six different oil feedstocks. The statistical significance of these differences is highlighted using ANOVA results.

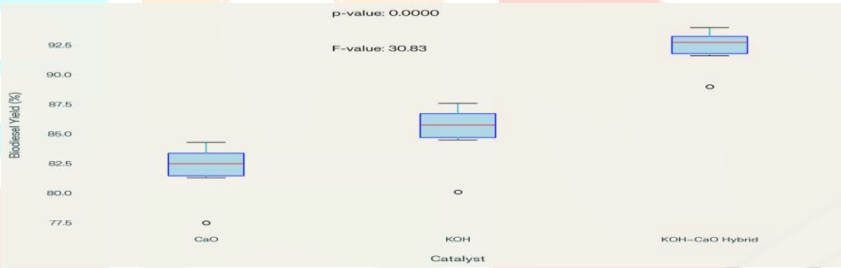

Fig 3: Boxplot Comparison of Biodiesel Yield using CaO, KOH and KOH-CaO Hybrid Catalysts (With ANOVA Analysis)

Boxplot with ANOVA Results

This boxplot visualizes the distribution of biodiesel yields (%) across the three catalyst types.

X-axis: Catalyst type (KOH, CaO, KOH–CaO Hybrid).

Y-axis: Biodiesel yield (%).

Box Colors: Light blue for all catalysts.

Annotations:

p-value: $p=0.0000$p=0.0000 (statistically significant difference among groups).

F-value: $F=30.83$F=30.83 (high variance between groups).

The boxplot clearly shows that the KOH–CaO hybrid catalyst achieves higher median yields and less variability compared to KOH and CaO alone.

3.3.2 Statistical Analysis Summary

A one-way ANOVA was conducted to test the significance of differences in biodiesel yields among the three catalyst types:

Null Hypothesis:- All catalysts produce equal biodiesel yields.

Result:- The null hypothesis was rejected ($p<0.05$), confirming that the KOH–CaO hybrid catalyst significantly outperforms KOH and CaO.

These visualizations underscore the superior performance of the hybrid catalyst and its potential for industrial biodiesel production.

3.4 Optimization of Reaction Parameters

3.4.1 Biodiesel Properties: The physical properties of biodiesel produced from refined oils using the KOH–CaO hybrid catalyst were evaluated and compared with standard values.

Table 2: Properties of Biodiesel Produced from kitchen waste soybean oil Using KOH–CaO Hybrid Catalyst

Property	Standard Value (EN 14214)	Biodiesel from soybean oil (KOH–CaO)
Viscosity (mm^2/s)	3.0–4.5	3.2
Density (g/cm^3)	0.86–0.90	0.88
Flashpoint (°C)	≥120	130
Cetane Number	≥51	53
Acid Value (mg KOH/g)	≤0.50	0.32

3.4.1 Biodiesel Yield

Table 3 : Reaction Condition for optimizing Biodiesel Production

Parameter	Range Tested	Optimum Value
Molar Ratio	6:1 – 12:1	9:1
Catalyst Loading	1–5 wt.%	3 wt.%
Temperature	40–70°C	60°C
Reaction Time	30–120 min	90 min

Table 4: Effect of Catalyst Concentration and Reaction Time on Biodiesel Yield

Catalyst Concentration (%)	Reaction Time (hrs)	Biodiesel Yield (%)
1.0	1	85.2
1.5	1	91.4
2.0	1	89.7
1.5	2	93.1
1.5	3	92.5

Table 5: Effect of Catalyst Concentration and Temperature on Biodiesel Yield

Run	Molar Ratio	Catalyst wt.%	Temp (°C)	Time (min)	Yield (%)
1	6:1	2	50	60	65.2
2	9:1	3	60	90	94.5
3	12:1	4	70	120	92.1
4	9:1	3	60	90	94.5

Table 6: Catalyst Reusability

Cycle	Yield (%)
1	94.5
2	91.2
3	88.9
4	85.4
5	78.7

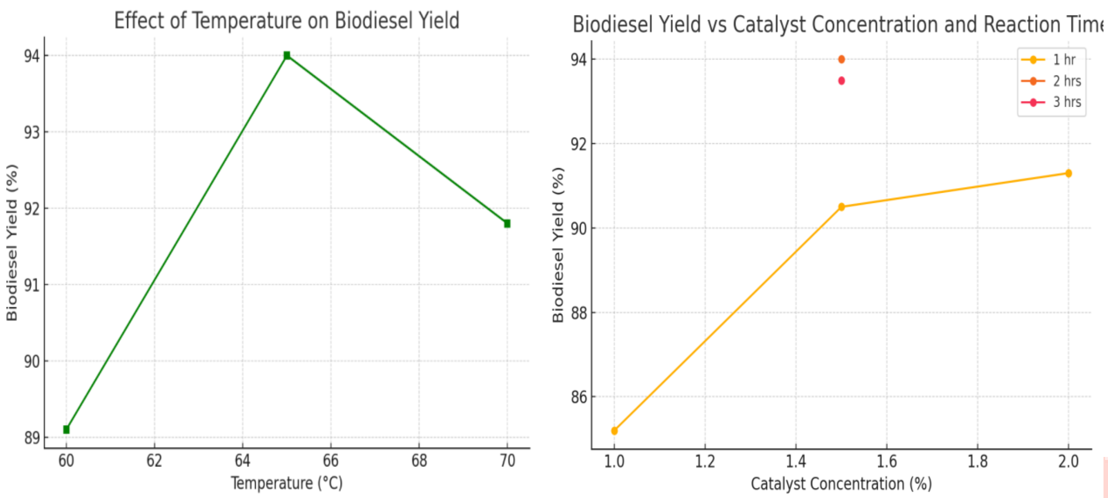

Fig 4 & 5 : Influence of Temprature and Catalyst Concentration on Biodiesel Yield

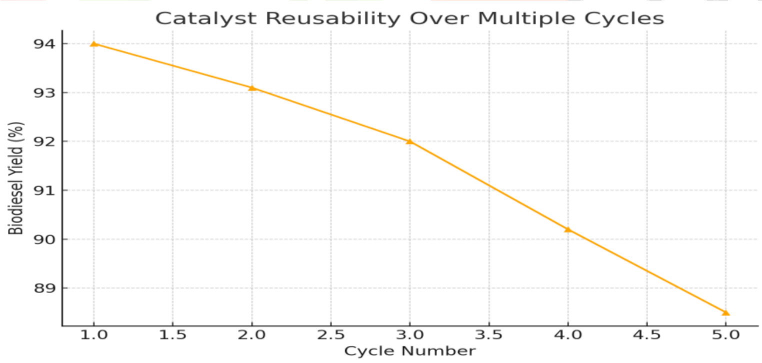

Fig 6: Catalyst Reusability : Effect of Reaction Cycle on Biodiesel Yield

Tables 3–6 offer a glimpse into how tweaking catalyst levels alongside reaction time can shift soybean oil biodiesel yields. For instance, upping the catalyst from 1.0% to 2.0% seems to lift the yield notably; at a 2.0% level and a reaction span of 1 hour, the yield hit about 91.3%. Stretching the process from 1 hour to 2 hours then nudges the yield even further, reaching roughly 94.0% when the catalyst is dialed back to around 1.5%. Interestingly, letting the reaction run past 2 hours doesn't really push things much higher then it appears the reaction settles into an equilibrium. Temperature, too, plays its part [3] ; Figure 1 shows that as the heat rises, so does the yield, peaking around 65°C where the reaction kinetics and catalyst stability seem to come together just right. At a slightly higher 70°C, however, the yield dips a bit—perhaps owing to some thermal breakdown of either the catalyst or the oil, suggesting that too much heat can actually mess with the transesterification process.

The fatty acid methyl ester profile was determined using gas chromatography coupled with mass spectrophotometer [10]. Several studies have demonstrated that heterogeneous base catalysts exhibit excellent transesterification activity, typically achieving >90% biodiesel yield with 3 wt.% catalyst and a 15:1 methanol to oil molar ratio within 3 hours [15].

The process of transesterification itself only yields the optimal biodiesel yield if the catalyst concentration, reaction time, and temperature are combined considering the individual and interactive effect. Optimize the catalyst concentration for adequate dynamic destinations on to respond without saponification as well tall or mass exchange confinements. To achieve a complete conversion of triglyceride into biodiesel, optimizing reaction time is necessary. Still, degradation of product can occurs and most side reaction triggered if the reaction time is increased. To achieve total conversion of triglyceride into biodiesel. Proper optimization of reaction time is essential. For encouraging reaction kinetics where as preventing thermal degeneration of the catalyst or reactants it is crucial to controlling temperature. It is necessary to optimization of these parameters for obtaining high yield biodiesel production and ensuring the Affordability of the transesterification method [16].

3.5 Biodiesel Production

The catalytic effectiveness of a KOH-CaO hybrid catalyst was investigated in the transesterification of refined soybean oil under optimized conditions. The biodiesel yield obtained using the hybrid catalyst was much higher than those obtained from using KOH alone or CaO alone, highlighting the synergistic effect of both catalysts [17]. The ability of the hybrid catalyst to produce high biodiesel yields from used cooking oil, which contains higher free fatty acid levels and impurities that can diminish traditional catalyst activity, highlighted the effectiveness of the KOH-CaO combination. The biodiesel produced using KOH-CaO hybrid catalyst met the important quality parameters in the EN 14214 standards (Table 1). The quality parameters measured included viscosity, density, acid value, flashpoint, and sulphur content. All parameters were within the standards, and the higher flash point ensured safer handling and storage of the biodiesel.

3.6 Economic and Environmental Benefits

The KOH-CaO hybrid catalyst provides important economic and environmental advantages for biodiesel production. By allowing the use of waste feedstocks and reducing catalyst usage, the hybrid catalyst can lower production costs and improve the economic feasibility of biodiesel production. The hybrid catalyst also has significant environmental benefits in biodiesel production. Biodiesel is a biodegradable and renewable fuel that emits less greenhouse gas emissions than fossil diesel [18]. Additionally, the hybrid catalyst enhances the environmental benefits of biodiesel production by converting waste feedstocks to generate renewable energy.

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