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Biodiesel synthesis from *Sisymbrium orientale* seeds oil using homogeneous and heterogeneous catalysts derived from food waste

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ABSTRACT

Biodiesel has become one of the most attractive alternative biofuels as a sustainable option for petroleum-derived diesel fuel. This research presents an innovative method for producing biodiesel from a non-edible plant source, Wild Samara (*Sisymbrium orientale)* seeds oil (SOSO), which is abundant in many countries. Production process was carried out via a transesterification reaction using two types of catalysts: a homogeneous KOH-based catalyst and a heterogeneous silica-supported calcium oxide ($CaO-SiO_2$) catalyst. CaO was prepared from eggshells, while silica was extracted from peanut shells. The catalyst was characterized using various analytical techniques such as FT-IR, FESEM, and XRD. Novelty of this study lies in its focus on improving production by examining the factors affecting biodiesel yield, including the ethanol-to-oil molar ratio, catalyst type and quantity, reaction temperature, and reaction time. Results indicated that maximum biodiesel yield reached (94.2%) when using (KOH) as catalyst, whereas higher yield of (98.5%) was achieved with heterogeneous catalyst. Optimal molar ratio [ethanol: oil] was [6:1], and the optimal amount of KOH catalyst was 1.5wt.% and 1wt.% for $CaO-SiO_2$. Optimal reaction temperature was 60 °C, while ideal reaction time was 1.5 hr. for KOH and 1hr. for $CaO-SiO_2$. for heterogeneous catalyst. Properties of produced fuel were analyzed using GC-MS and FT-IR techniques. Results showed that biodiesel produced using $CaO-SiO_2$ catalyst had excellent physical and chemical properties. Compared to its counterpart prepared using KOH, this study highlights potential for achieving one of sustainable development goals by exploiting non-food natural resources and organic waste to produce environmentally friendly biofuel.

Keywords: biodiesel, *Sisymbrium orientale*, catalysts, peanut shells, transesterification, fuel characterization.

INTRODUCTION

Sisymbrium orientale is a species of flowering plant in Brassicaceae family, commonly known as Indian hedge mustard, eastern rocket, or shalwi. It is native to Europe, Asia, and North Africa and can be found in most parts of the world as an imported species and, certain regions, it commonly grows as a roadside weed. This annual herb features a branched, hairy stem that can reach approximately 30 cm in height. The basal leaves are deeply lobed or consist of toothed leaflets, while the upper stem leaves have lance-shaped blades with small, separate lobes near their bases. At the top of the stem, clusters of flowers with pale yellow petals-each measuring up to 1 cm in length-are found. As an annual, it blooms in winter or early spring, then it produces long seed pods (Silique) bearing dry seed chains that open upon maturity for the plant to spread naturally. These seeds are not used as a food source for humans or as direct animal feed. Because the seeds contain a high percentage of fatty acids (oleic acid, linoleic acid, erucic acid), this makes it suitable for producing biodiesel [Rahman et al., 2024; Lauber et al., 2018].

Biodiesel is a renewable biofuel produced through the chemical conversion of alcohol with vegetable oils or animal fats. Its renewable potential, biodegradability, and low toxicity make it a practical alternative to petroleum [Karmakar and Haldar, 2019; Narayanan et al., 2024]. Over the past 25 years, biofuels such as biogas, biodiesel, and bioalcohol have gained considerable attention as promising alternatives to conventional fossil fuels, primarily due to the environmental and health risks associated with fossil fuel use and their contribution to climate change [Callegari et al., 2020]. Monoalkyl esters of long-chain fatty acids, commonly known as biodiesel, have been regarded over the past few decades as a promising alternative to help reduce the reliance on conventional diesel fuels [Razzaq et al., 2020]. Biodiesel is a natural, environmentally friendly fuel that burns cleanly, is non-toxic, and free from sulfur and aromatic compounds. It is a prominent, economically viable, and technically feasible alternative fuel. Its ease of use and high combustion efficiency are demonstrated by its ability to burn in the same engine with few mechanical modifications [Khan et al., 2020]. Biodiesel is produced from a variety of sources, including vegetable oils, microalgae, animal fats, edible waste oils, and surplus cooking oils generated from both household and commercial activities [Saeed et al., 2021]. Non-edible vegetable oils have been used as preferred raw materials for the manufacture of biofuels [Gardy et al., 2019].

Biodiesel raw materials must meet two basic requirements: a wide production scale and a low production cost [Cavalheiro et al., 2021]. Its production is mainly carried out by transesterification using homogeneous or heterogeneous (basic or acidic) catalysts. Due to some of the distinctive problems associated with use of homogeneous catalysts such as soap formation, difficulty of separation, and equipment corrosion, biodiesel is mainly produced by transesterification using homogeneous or heterogeneous (basic or acidic) catalysts. Heterogeneous catalysts are used because of their ease of separation and reusability [Nath et al., 2019]. In recent research, heterogeneous catalysts based on agricultural and food waste have gained increasing attention as a potential green catalyst in transesterification biodiesel production because they are renewable, readily available and low cost, such as almond oil [Fadhil and Mohammed, 2018], coconut shells [Miladinovic et al., 2020], orange peels [Changmai et al., 2020], Mandarin (*Citrus reticulata*) seeds [Fadhil, 2020], banana peels [Etim et al., 2022] and so on.

Literature references explain the different methods for preparing biodiesel from different raw materials, methods, and catalysts, as it can be produced from any oil source [Ameen et al., 2022]. Biodiesel was produced from non-edible seed oil (*Cucumis melo* var. agrestis) using MgO as catalyst at a rate of (2 wt.%) at a temperature of (60 °C) and a ratio of [methanol: oil] [9:1]. The biodiesel yield was (93%) and it was characterized using gas chromatography and mass spectrometry (CG-MS), Fourier transform infrared spectroscopy (FTIR) and nuclear magnetic resonance (NMR). Produced biodiesel was characterized by a density of (0.800 kg/L), viscosity of (4.23 cSt), cloud point of (-12 °C), pour point of (-7 °C), sulfur content of (0.0001%), flash point of 73.5 °C and total acid no. (0.167 mg KOH/g). It was thus a promising step towards a biorefinery for non-food biomass.

Gupta et al. (2022) studied the potential for producing biodiesel from rapeseed oil, which represents 80% of the European fuel market. The study showed that the produced fuel has an annual global warming potential (GWP) of 2.63 and 2.88 t CO_2-eq biodiesel, thus reducing CO_2 emissions. Mondal and Mizanur Rahman (2024) were able to find a suitable raw material for producing biodiesel, which is linseed oil, through the esterification reaction using NaOH catalyst. They studied the factors affecting the reaction, such as the molar ratio of alcohol to oil, and found that the best ratio was [6:1], the best amount of catalyst (1.5 g), a reaction time of two hours, and a temperature of (60 °C), which were within the range of the standards (ASTMD975 and ASTMD6751). It can be used as an alternative fuel in diesel engines by mixing it with diesel in different proportions.

Kurczynski and Wcislo (2024) were able to produce biodiesel from hemp oil and compare its properties with biodiesel extracted from rapeseed according to the EN14214 standard. They found that the produced fuel contains a considerable proportion of esters of linoleic and linolenic acids, which are susceptible to oxidation. This is more than what was obtained from rapeseed oil. Yazilitas et al. (2024) produced biodiesel from non-edible hempseed (*Cannabis sativa.* L.) oil and used the response surface method to find the best molar ratio between methanol and oil and found that best ratio was [7.41:1] and the best KOH catalyst concentration was (0.80 wt.%), reaction time (62.83 min), optimum reaction temperature (61.92 °C) and yield (95.57%). This enhanced the potential of using hemp seed oil as a raw material for biodiesel production.

Jamil (2024) investigated the potential for producing and enhancing biodiesel from castor oil (*Ricinus communis* L.) using (NaOH, KOH) as solid base catalysts. It was found that the fatty acid content in castor oil prior to esterification was 22.4% mg KOH/g. The research examined the effects of alcohol-to-oil ratio, reaction time, temperature, and catalyst concentration on the biodiesel yield. The highest yields were obtained using NaOH (94.6%) and KOH (96.2%) catalysts. The resulting biodiesel was characterized as sustainable and environmentally friendly for industrial applications.

Razaq et al. (2024) produced biodiesel from poppy seed oil (*Papaver somniferum*) by refining poppy seeds using H_2SO_4 pre-treatment before esterification process in addition to a single-step alkali-catalyzed transesterification using KOH and methanol. With the help of response methodology, the process variables (temperature, time, catalyst amount, methanol to oil ratio) were optimized to produce maximum yield. Highest yield of (94.87%) was obtained in 90 min, 60 °C, catalyst concentration (0.25 mg) and alcohol to oil ratio (3%). The properties of the produced biodiesel were measured and compared with (ASTMD6751). GC-MS results revealed the presence of 12-octadecadienoic acid methyl ester.

Nawaz et al. (2024) were able to produce biodiesel from potato stalk. Response surface methodology (RSM) and machine learning techniques were effectively employed to model the pyrolysis of potato stalks, enabling the evaluation and optimization of key process parameters. Among these, temperature emerged as the most influential factor, whereas nitrogen flow rate had the least impact. Best bio-oil production (45.72%), highest biochar production (26.95%) were achieved at 525 °C, a heating rate of 75 °C/min, and a nitrogen flow rate of 150 mL/min.

Anekwe-Nwekeaku et al. (2025) studied production of biodiesel from *Sesamum indicum* (S. indicum), *Cyperus esculentus* (C. esculentus), and *Colocynthus vulgaris* (C. vulgaris) oils through H_2SO_4 catalyzed esterification process and analyzed the properties of the produced fuel and its blends with hydrocarbon diesel. The results showed that the conversion efficiency exceeded (80%) for biodiesel from cyperus and colocynth. It was noted that all types of biodiesel showed a significant decrease in acid emissions, with biodiesel *C. vulgaris* recording lowest value of (0.0015 g/dm^3). In addition, blending these types of biodiesel with carbon diesel significantly improved fuel efficiency and emissions.

This research aims to produce biodiesel from a new and ideal raw material, *Sisymbrium orientale* seed oil, through a catalytic esterification process using two types of catalysts: homogeneous basic (KOH) catalyst and heterogeneous (CaO-SiO_2) catalyst based on calcium oxide (CaO) prepared from eggshells and supported by silica (SiO_2) prepared from peanut shells (food waste) using ethanol. The effects of catalyst type and concentration, ethanol to oil molar ratio, reaction temperature, and reaction time on yield of produced biodiesel were studied. Biodiesel was characterized using GC-MS and FT-IR techniques. The properties of the produced biodiesel were determined according to ASTM standards.

MATERIALS AND METHODS

Materials

Eggshells and peanut shells were collected from food waste. Ethanol pure 99% (C_2H_5OH) was supplied by B.D.H & Tedia. n-hexane, hydrochloric acid (HCl), H_2SO_4, and chloroform ($CHCl_3$) were purchased from Fluka. potassium hydroxide (pure 95%)(KOH), used as a basic catalyst, and sodium hydroxide (pure 96%) were purchased from Merck. Chemicals of analytical grade were used in their received form, without additional purification procedures.

Instruments

XRD diffraction spectroscopy Thermo (American), field emission scanning electron microscopy from Thermo Fisher FEI Quattro FE-SEM (made in Japan). Fourier transform infrared spectroscopy (FTIR) an Alpha II FT-IR Spectrometer (Bruker-Germany, 2024). The infrared spectrum measurements of all prepared catalyst were recorded using (FTIR spectrophotometer) in the region limited to (400–4000 cm^{-1}), Gas chromatography-mass spectrometry (GC-MS) to characterization prepared biodiesel.

Mass spectrometer – Agilent 5977A MSD, software – Mass Hunter GC/MS Acquisition and mass hunter qualitative program, ion source temperature – 230 °C, quadrupole temperature – 150 °C, interface temperature – 290 °C, solvent cut time – 4.00 min, acquisition time – start at 4.00 min, end between 35.00–40.00 min, acquisition mode – scan, scan speed – 1562 (N_2 gas), scan range (m/z) – 35 to 650, gas chromatograph – Agilent 7890B, initial temperature – 40 °C, hold for 5 minutes, ramp rate – 10 °C/min, injection temperature – 290 °C, injection mode – pulsed, splitless, flow control mode – constant flow, pressure – 7.0699 psi, column flow – 1 mL/min, total gas flow – 19 mL/min, injection volume – 1 μL, purge flow – 3 mL/min, column type – HP-5MS (5% phenyl methyl siloxane), 30 m length × 0.25 mm ID × 0.25 μm film thickness.

Procedure

Oil extraction

In this research, wild Samara seed oil, scalled (*Sisymbrium orientale*) seed oil (SOSO), was used to prepare biodiesel fuel because it contains suitable amounts of oils, and also because this plant is widely spread in Nineveh Governorate. Therefore, its seeds were collected in the summer of 2024 from different areas, especially in open lands or on the edges of fields in Nineveh Governorate. The seeds were separated, cleaned of impurities, and ground using an electric grinder. Oil was extracted from ground seeds using (Soxhlet) extraction apparatus connected to (1 liter) round bottom flask, and appropriate solvent was added to it in a ratio of (3:1) (solvent: seeds). Hexane solvent was used due to its suitability for extraction after the study and comparison with other available solvents such as petroleum ether solvent, which had a lower oil extraction rate than hexane, then, the thermal escalation was carried out for 24 hours using a water bath at the boiling point of the solvent, then the product was filtered and the hexane was recovered using a distillation device under vacuum pressure and at a temperature of (40 °C). Then, percentage of extracted oil was calculated. Figure 1 shows the shape of the plant, seeds and extracted oil.

Preparation of silica-supported calcium oxide catalyst CaO-SiO$_2$

Eggshells and peanut shells were collected and cleaned of various impurities.

- First: Preparing calcium oxide from eggshells. Eggshells were treated as shown in Figure 2.
- Second: Preparing silica from peanut shells. Silica was prepared from peanut shells using the steps shown in Figure 3.
- Third: Preparation of calcium oxide CaO supported by silica SiO$_2$. The preparation steps are shown in Figure 4.

Transesterification reaction

SOSO esterification process was carried out by placing a suitable amount of oil in a 250 ml three-neck flask connected to a condenser and leaving it on a water bath to reach the required temperature for the reaction. A specified amount of catalyst solution (CaO-SiO$_2$, KOH) dissolved in ethanol at a molar ratio of [6:1] [ethanol : oil] was prepared and added to preheated oil. Mixture was then reheated with continuous stirring using a magnetic stirrer for one hour at 60 °C [Slani and Canakci, 2008; Anastopoulos et al., 2009], After reaction was completed, mixture was transferred to a separating funnel and left for (24 hrs.). Two layers were observed to form, upper layer representing ethyl ester and lower layer representing glycerol. Ethyl ester layer, which represents biodiesel, was separated and placed in a distillation apparatus under vacuum at (30 °C) to recover unreacted ethanol. Ethyl ester was then washed with preheated distilled water (100 °C) to remove excess ethanol and impurities, hot water increases the solubility of ethanol and impurities in it, thus making it easier to separate them from the ethyl esters, which are usually less soluble in hot water. Heat also helps to accelerate the physical reaction between water and soluble components, making

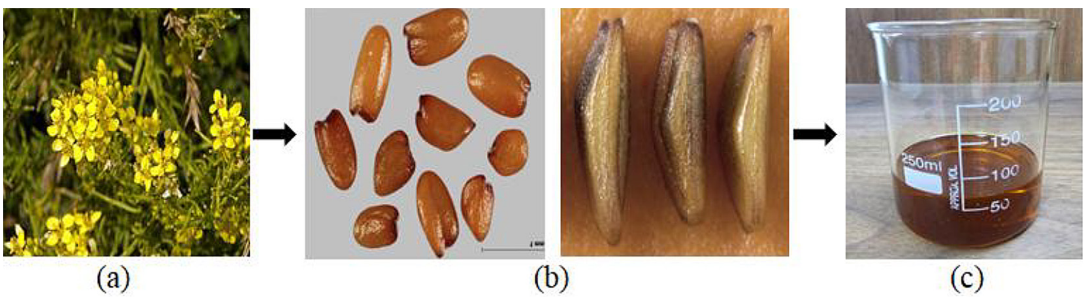

Figure 1. (a) The shape of the *Sisymbrium Orientale* plant (b) The seeds of the plant (c) The extracted biodiesel fuel

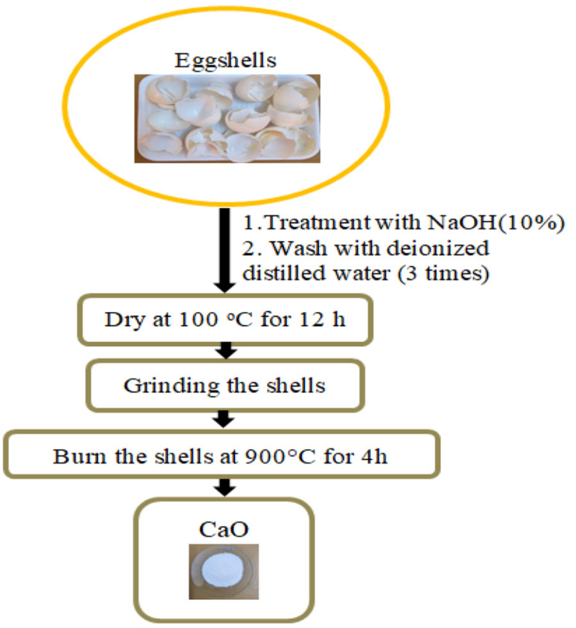

Figure 2. Preparation scheme for calcium oxide (CaO) from eggshells

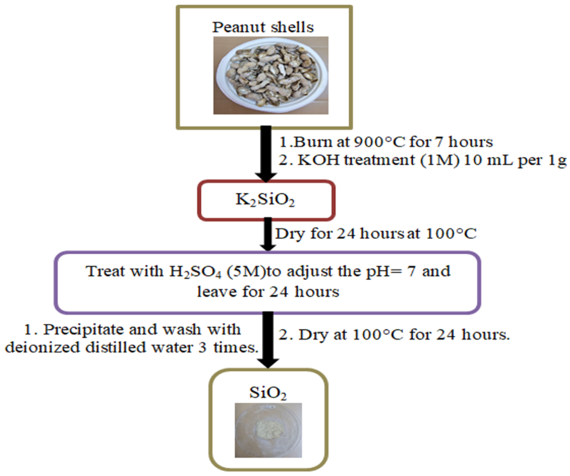

Figure 3. Preparation scheme for silica (SiO_2) from peanut shells

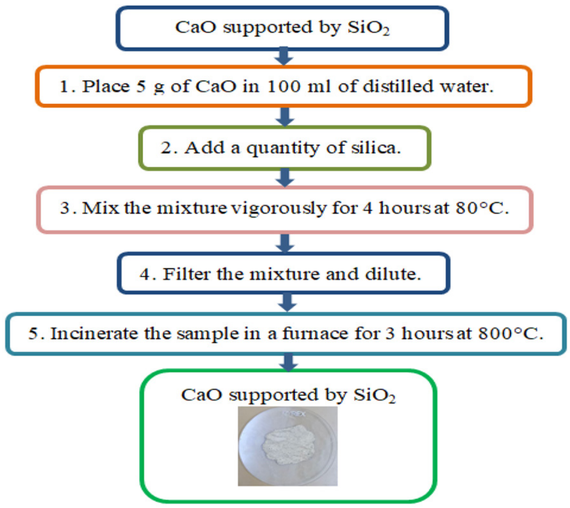

Figure 4. Scheme for CaO supported with SiO_2

washing more efficient (hot water washing is a method of purifying the product by taking advantage of the solubility difference between esters, ethanol, and impurities).

The yield was calculated using Equation 1 [Onukwuli et al., 2017]:

$$\textit{Biodiesel yield}\ (\%) = \frac{\textit{Weight of the purified ethyl esters}}{\textit{Weight of oil used}} \times 100 \quad (1)$$

The factors affecting the transesterification process were studied: the ethanol to oil molar ratios (2:1, 4:1, 6:1, 8:1, 10:1) were used, the catalyst quantities were used at weight ratios of (1.5, 1, 0.5), and the reaction was carried out at different times (1.5 h, 1 h, 0.5 h) and different reaction temperatures (50 °C, 60 °C, 70 °C).

Evaluation of physical and chemical properties

The properties of biodiesel produced from (SOSO) were quantitatively determined and compared with ASTM D such density at 15.6 ASTM D4052-91, kinematic viscosity at 40 °C ASTM D445, flash point °C ASTM D93, acid value (mg KOH/g oil) ASTM D664, saponification value (mg KOH/g oil) ASTM D5555-95, iodine number mg I_2/100 oil(Hanus method), cloud point °C ASTM D2500, pour point °C ASTM D2500, Cetane number ASTM D613, conradson carbon residue ASTM D4530.

RESULTS AND DISCUSSION

Feedstock profiles of SOSO

This study investigates the use of SOSO as a potential feedstock for biodiesel production, given its fatty acid composition. Composition of fatty acids in oil plays an important role when using biodiesel as a fuel in diesel engines. Esters derived from saturated fatty acids exhibit higher cetane numbers, better oxidation stability, but have inferior flow characterties at low temperatures compared to esters from unsaturated fatty acids [Bouaid et al., 2024, Pradana et al., 2024], Table 1 shows the acid composition of SOSO. It is evident that the unsaturated fatty acid content, at 78.85%, is higher than that of some vegetable oils, as shown in the table below. It is also much

Table 1. Fatty acid composition of SOSO

Fatty acid (wt.%)	SOSO	Sunflower oil[a]	Pearl millet oil[b]
C13	2.73	-	-
C14	0.26	-	-
C15	0.52	-	-
C16:0	5.90	7.29	21.90
C16:1	0.20	-	0.10
C18:0	1.90	13.55	3.40
C18:1	12.10	-	-
C18:2	16.60	58.98	73.90
C18:3	36.80	0.12	-
C19	0.76	-	-
C20:0	1.70	0.33	0.30
C20:1	9.20	-	0.30
C22:0	9.50	0.93	-
C22:1	0.20	-	-
C24:0	0.90	-	0.10
Other	0.73	-	-
Total saturated FA	20.00	22.10	25.70
Total unsaturated FA	78.85	77.89	74.30
Total polyunsaturated FA	55.00	59.10	73.90
Total monounsaturated FA	21.90	18.79	0.40

Note: Sunflower oil[a] Ref. [Niyas and Shaija, 2022]; Pearl millet oil[b] Ref. [Perveen et al., 2021].

higher than its saturated fatty acid content 20.0%. The polyunsaturated fatty acid content was lower than the monounsaturated fatty acid content.

Biodiesel yield

Biodiesel yield using two types of catalysts: homogeneous basic catalyst (KOH) and heterogeneous catalyst ($CaO-SiO_2$) on oil (SOSO). The maximum biodiesel yield was achieved using (KOH) as basic catalyst, based on parameters such as molar ratio [ethanol: oil] [6:1], catalyst amount by weight (1%), temperature (60 °C), and reaction time of (1 hour) was (90.2%). Maximum biodiesel yield obtained using ($CaO-SiO_2$) as the heterogeneous catalyst under the same parameters was 98.5%.

Properties of (SOSO)

The chemical and physical properties of SOSO were determined from Table 2, we note that the oil density is comparable to some other oils. It is observed that the kinematic viscosity of SOSO is lower compared to other vegetable oils, This may be attributed to differences in the chemical composition of the oil under study compared to other types of oils. One of the most critical chemical properties of the oil is its acidity value, as it determines the appropriate method for converting the oil into biodiesel. In this study, the acidity value was found to be 2.74 mg KOH/g of oil, which is lower than the values reported for other vegetable oils. which indicates the possibility of converting the oil into biofuel through the transesterification reaction in the presence of a basic catalyst. As for the soaping value, which is less than that recorded for some other types of vegetable oils. Iodine value of SOSO (121.7 mg I_2/100 g oil) is lower than that of sunflower and pearl millet oils, likely due to their greater polyunsaturated fatty acid content, as shown in Table 2.

Characterization of the catalyst

The catalyst prepared from eggshells and supported by peanut shells was characterized using (FTIR-FESEM-XRD) techniques as shown in Figure 5. FTIR spectrum in Figure 5 confirms the presence of both calcium oxide (CaO) and calcium carbonate ($CaCO_3$). Characteristic calcium oxide

Table 2. Physical and chemical specifications of SOSO compared to the specifications of oils

Property	SOSO	Sunflower oil	Pearl millet oil
Density @ 15.6	0.901	0.834	0.813
Kinematic viscosity @ 40 °C	20.40	22.60	25.01
Flash point (°C)	268	274	-
Acid value (mg KOH/g oil)	2.74	2.92	-
Saponification value (mg KOH/g oil)	120.2	177	192
Iodine number mg I_2/100 oil	121.7	132	127
Cloud point (°C)	-3	2.5	4.4
Pour point (°C)	-6.2	-7.7	-5.1
Cetane number	53.4	47.4	46.2
Conradson carbon residue(%)	0.108	-	-

(Ca-O) vibrations appear at 871 cm^{-1}, 682.50 cm^{-1}, and 407.13 cm^{-1}, while additional peaks indicate traces of carbonate species. Surface wetting is also evidenced by oxygen (O-H) stretching bands at 3638.07 cm^{-1} and 3533.50 cm^{-1}, due to adsorbed water or the hydroxyl groups characteristic of calcium oxide [Sovova et al., 2021].

The characteristic peaks of $CaCO_3$ at 1390.58 cm^{-1} and 871 cm^{-1} confirm the presence of calcite, a common crystalline carbonate form. The peak at 1786.83 cm^{-1} also supports the presence of carbonate species, consistent with incomplete calcination. Furthermore, the peaks at 2359.95 cm^{-1} and 2161.94 cm^{-1} may result from impurities such as organic residues, adsorbed carbon species, or other surface functional groups that may be associated with the aliphatic C-H stretching characteristic of trace organic compounds. These additional peaks, not characteristic of pure calcium carbonate or pure calcium carbonate, may indicate minor contamination or incomplete calcination during sample preparation. As for SiO_2, an asymmetric stretching vibration band appears at 1023.50 cm^{-1} and a bending vibration band at 438.34 cm^{-1}, which is due to the Si-O-Si bond. Infrared spectroscopy of CaO-SiO_2 revealed a band at 1084.43 cm^{-1}, which is due to the Si-O-Si bond, with a slight shift or displacement when supported by CaO due to structural distortion. A band at 871.33 cm^{-1} is due to the symmetric Si-O-Si stretching vibration.

X-ray diffraction (XRD) analysis also supports the observed IR peaks. The Figure 5 shows CaO calcined at 900 °C for four hours, where we notice the main diffraction peaks of calcium oxide 29°, 36°, 39°, 46°, 48°. As for the XRD analysis of SiO_2, the main diffraction peaks appear at 23°, 29°, 43°,. On the other hand, the peaks were observed for the CaO-SiO_2 catalyst at 29°, 39°, 47°.

Optimization of SOSO reaction parameters using KOH and CaO-SiO_2 catalysts

Effect of ethanol to oil ratio on biodiesel yield

Transesterification uses alcohol as main reactant that affects the BD yield. To study this parameter, different molar ratios of [ethanol : oil] (2:1, 4:1, 6:1, 8:1, 10:1) were tested and other parameters were determined as constants such as the amount of catalyst (1 wt.%) at (60 °C) and a reaction time of one hour. Figure 6 shows that BD yield increases with increasing molar ratio of ethanol. Maximum BD yield was obtained using KOH catalyst (90.2%) at a ratio of [6:1] and maximum biodiesel yield was obtained using CaO-SiO_2 catalyst (98.5%) at a ratio of [6:1]. This is because as ethanol concentration increases, the reaction starts to move towards equilibrium, so the molar ratio of [6:1] was chosen as the optimum. Otherwise, if the ethanol to oil ratio is increased beyond the optimum, BD yield will decrease. This is an indication of the reaction being inhibited by the increased solubility of glycerin in the reaction solution due to the increased alcohol to oil ratio. This increase makes the solution more complex, which makes the separation of glycerin from the reaction solution difficult.

Effect of catalyst amount on the yield of biodiesel

The amount of catalyst was evaluated as second parameter influencing biodiesel production efficiency. Different amounts of catalyst were taken, ranging from (0.5, 1, 1.5 wt.%), keeping other parameters constant. It was noted that when using KOH catalyst, when the amount of catalyst in the reaction was less than (0.5 wt.%), no BD production was obtained. Amount of catalyst

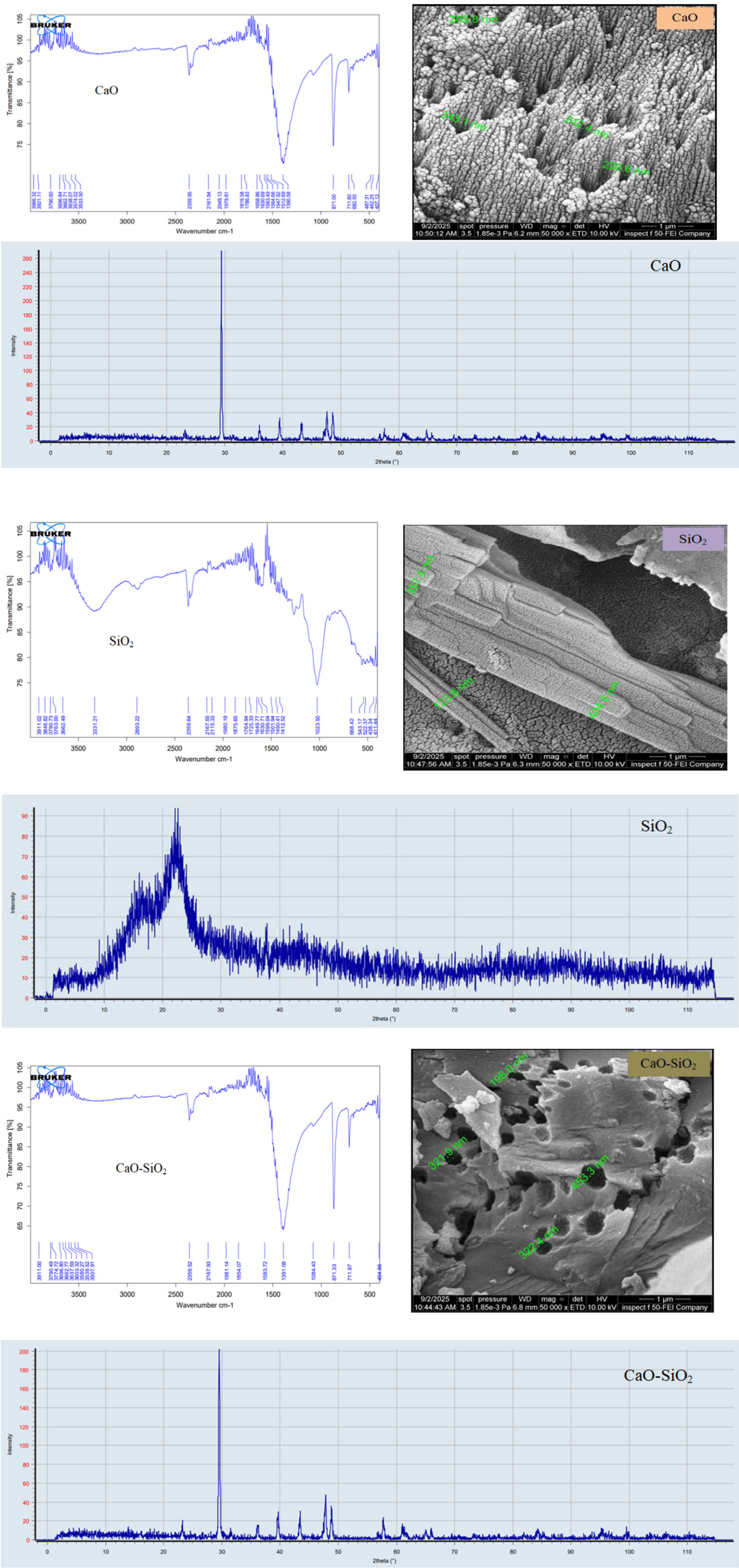

Figure 5. Characterization of catalyst FTIR, XRD and FESEM

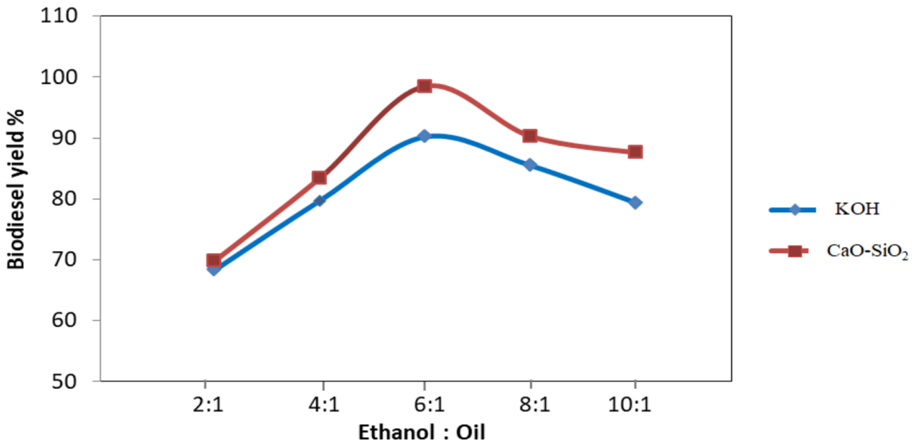

Figure 6. Biodiesel yield on different ethanol to oil ratio

was changed to (1.5 wt.%) and yield increased from (64.8%) to (92.5%). An increase in catalyst amount was associated with enhanced catalytic activity and improved conversion of triglycerides into biodiesel fuel. Consequently, this amount was deemed optimal. When using CaO-SiO_2 catalyst, the biodiesel yield was observed at (0.5 wt.%), which was (69.3%). When the amount of catalyst was increased (1wt.%), the yield became (98.5%). When the amount of catalyst was increased to (1.5 wt.%), the yield decreased to (93.2%) due to the increase in soap formation. Therefore, the optimal amount for this catalyst is (1 wt.%), as shown in Figure 7.

Effect of reaction time on biodiesel yield

To improve biodiesel production, the reaction time was studied at different times (0.5 h, 1 h, 1.5 h). The ratio of ethanol to oil was considered [1:6], the amount of KOH catalyst (1.5 wt.%), and the catalyst (1 wt.%) CaO-SiO_2, and a constant temperature of (60 °C). An increase in reaction time from one hour to one and a half hours was found to improve the efficiency of the biodiesel production process, a higher yield (94.2%) could be obtained for KOH due to the increased time given for complete conversion of the reactant. Therefore, the optimal reaction time was considered to be 1.5 hours (KOH) and 1 hours (98.5%) for the CaO-SiO_2 catalyst (CaO-SiO_2). Figure 8 shows the effect of reaction time on biodiesel yield.

Effect of reaction temperature on biodiesel yield

The effect of reaction temperature was studied at different temperatures (50 °C, 60 °C, 70 °C) and with other conditions fixed. It was observed that with increasing the temperature from 50 °C to 60 °C, the yield increased from (78.2) to (94.2) for the KOH catalyst and from (85.4) to (98.5) for the CaO-SiO_2 catalyst. This variation in yield can be attributed to the solubility of the reactants. It was observed that at 50 °C, both reaction kinetics and solubility decrease, leading to a reduction in biodiesel yield.

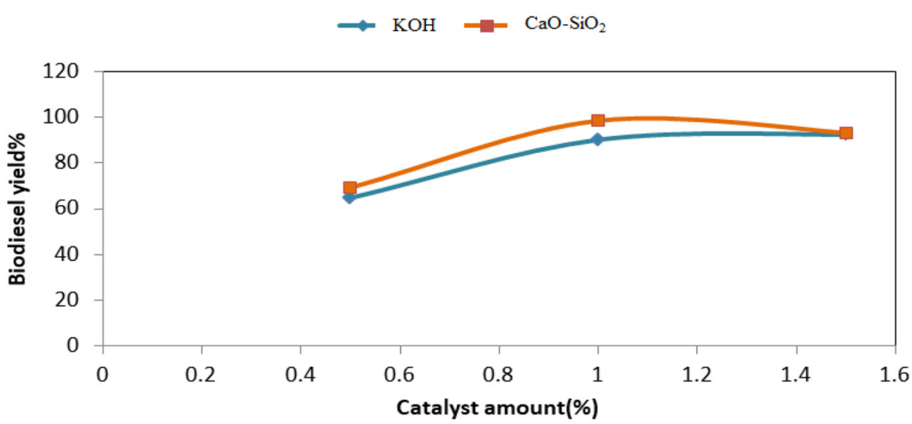

Figure 7. Biodiesel yield using different amounts of catalyst%

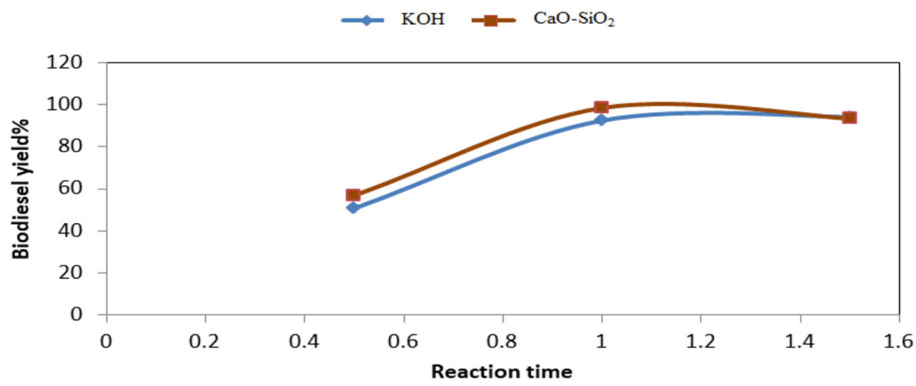

Figure 8. Biodiesel yield on different reaction time

However, with increasing temperature to 60 °C, the reaction kinetics and solubility increase and the maximum yield is obtained. When the reaction temperature was raised to 70 °C, a decline in biodiesel yield and an increase in soap formation were observed. As a result, 60 °C was determined to be the optimum temperature. Figure 9. Effect of temperature.

Fuel properties of SOSO biodiesel

The performance and emission characteristics of diesel engines are highly dependent on biodiesel fuel quality thus, it must be assessed in accordance with standard methods. Table 3 shows characteristics of the produced biodiesel, and for comparison purposes, it was compared with production of biodiesel from sunflower oil and used cooking oils [Fadhil and Abdulahad, 2014]. Density is a critical property of biodiesel, as it directly affects fuel injection systems, which operate on a volumetric basis. Consequently, fuels with higher density deliver a slightly greater mass of fuel [Demirbas, 2009; Mahmood and Al-Yaqoobi, 2024]. The densities of SOSOBD, measured at 0.871 and 0.824 g/cm³, are comparable to those of biodiesel derived from sunflower oil and used cooking oils. Furthermore, these values fall within the acceptable range specified by ASTM standards, which set a maximum allowable density of 0.9000.

The kinematic viscosity of biodiesel is significantly influenced by the raw material used. It should be maintained as low as possible because high viscosity leads to poor fuel spray atomization and decreased precision in fuel injector operation [Demirbas, 2009]. The kinematic viscosities of SOSOBD were measured at 4.89 mm²/s and 4.63 mm²/s, values close to that of SFOBD (5.11 mm²/s) and lower than those reported for WCOBD (7.01 mm²/s).

The iodine value (IV) is a measure of fuel unsaturation, which significantly influences fuel oxidation and the formation of deposits in diesel engine injectors. Biofuels rich in polyunsaturated fatty acids are more susceptible to oxidation due to the presence of numerous double bonds, leading to the formation of free radicals and harmful byproducts that reduce fuel quality. They must be

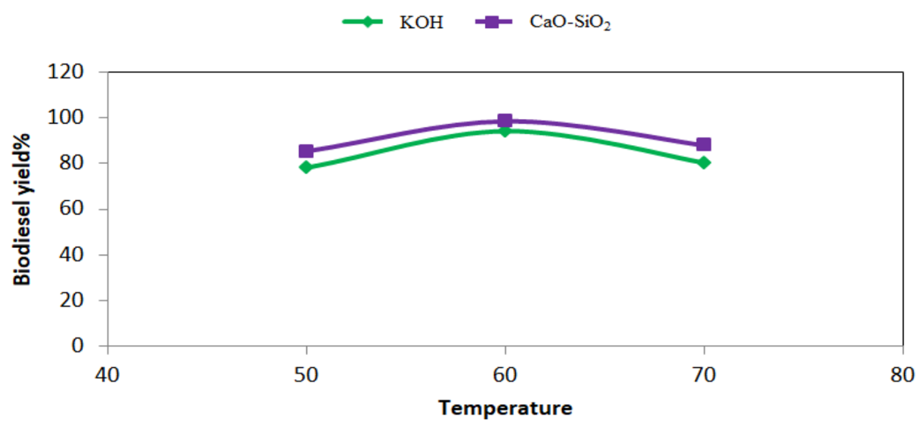

Figure 9. Biodiesel yield on different temperature

treated with antioxidants and stored under appropriate conditions) [Fadhil and Abdulahad, 2014]. The iodine values for SOSOBD oil were measured at 103 mg I_2/100 g oil and 101 mg I_2/100 g oil, closely matching those of SFOBD and WCOBD oils, indicating an acceptable level of unsaturation. Flash point, defined as the temperature at which released vapors ignite upon exposure to a flame under specified test conditions, is a critical safety parameter during fuel storage and transportation [Fadhil and Abdulahad, 2014]. The flash points of SOSOBD were recorded at 117 °C

Table 3. Evaluation of SOSO Biodiesel Properties in Relation to Biodiesel Standards

Property	SOSOBD KOH catalyst	SOSOBD used CaO-SiO_2 catalyst	SFOBD	WCOBD
Yield%	94.2	98.5	92.0	91.70
Density @ 15.6	0.871	0.824	0.8889	0.8911
Kinematic viscosity @ 40 °C	4.89	4.63	5.11	7.01
Flash point (°C)	117	116	115	170
Acid value (mg KOH/g oil)	0.17	0.15	0.05	0.37
Saponification value (mg KOH/g oil)	201	200	201	202
Iodine number mg I_2/100 oil	103	101	110	106
Cloud point (°C)	-4	-6	0	0
Pour point (°C)	-7	-8	-9	-7
Cetane number	54	57	-	-
Conradson carbon Residue (%)	0.039	0.035	0.003	0.097

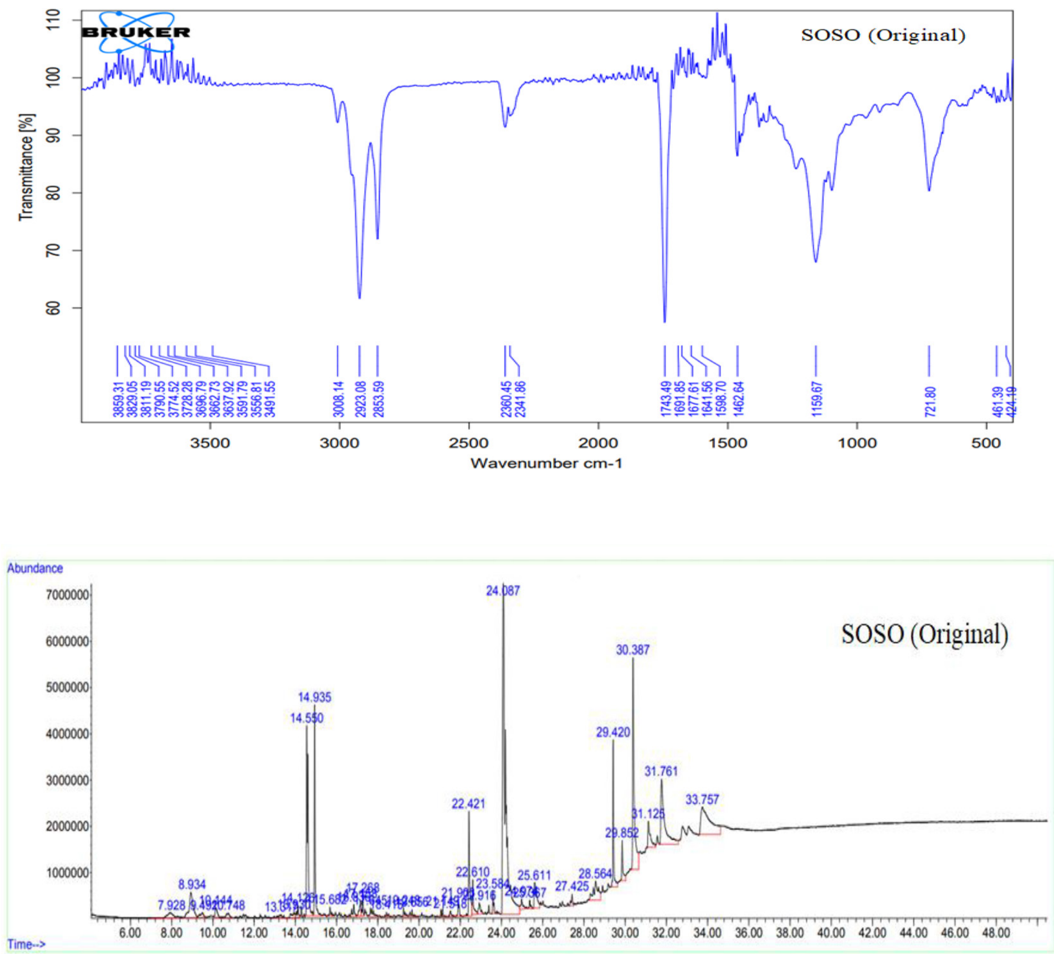

Figure 10. FT-IR spectra and GC-MS of SOSO

and 116 °C, values comparable to SFOBD and slightly lower than those reported for WCOBD.

The acid value is used to determine the free fatty acid content in biodiesel oil. Elevated acid values may result from incomplete esterification or from oxidative degradation occurring during storage [Ong et al., 2013; Fatah et al., 2025]. Values for SOSOBD are (0.17) and (0.15), which are lower than those obtained for WCOBD. The flow characteristics of biodiesel can be determined by the cloud point and pour point. The cloud and pour point of SOSOBD were (-6), (-4), and (-7), (-8) °C, respectively, which are close to those obtained for SFOBD and WCOBD. Carbon residues were determined using Conradson method. carbon residue values for SOSOBD obtained with both catalysts were within satisfactory limits.

The ignition quality of diesel fuel is commonly assessed by its cetane number, which indicates the ignition delay time after fuel injection into the combustion chamber [Bejene et al., 2024; Mahmood et al., 2024]. A higher cetane number corresponds to a shorter ignition delay and better combustion performance. Fuels composed of longer-chain, saturated fatty acid molecules tend to exhibit higher cetane numbers. Consequently, biodiesel derived from animal fats typically has a higher cetane number compared to that produced from vegetable oils [Demirbas, 2009]. The calculated cetane index of SOSOBD is (54) and (57).

Biodiesel characterization

The biodiesel samples prepared from SOSO catalyzed with 1.5% KOH and 1% CaO-SiO_2 were characterized by FTIR, GC-MS techniques as shown in Figure 10–12.

The biodiesel analysis results obtained via GC-MS indicate that the fatty acids present in the oil were successfully converted into their corresponding esters. The identified ester types correspond to the original fatty acids, confirming that the oil underwent effective conversion into biodiesel and that the esterification process was successful.

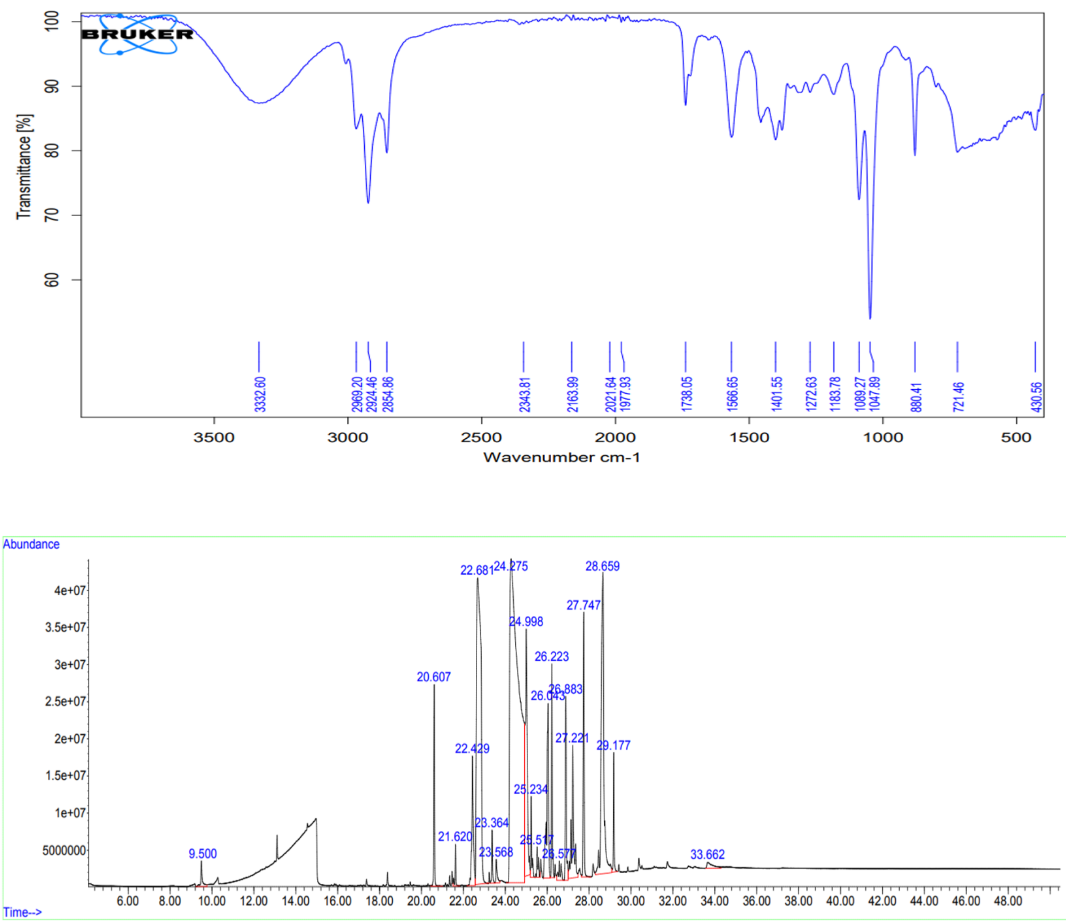

Figure 11. FTIR spectra and GC-MS of biodiesel prepared by transesterification using KOH catalyst

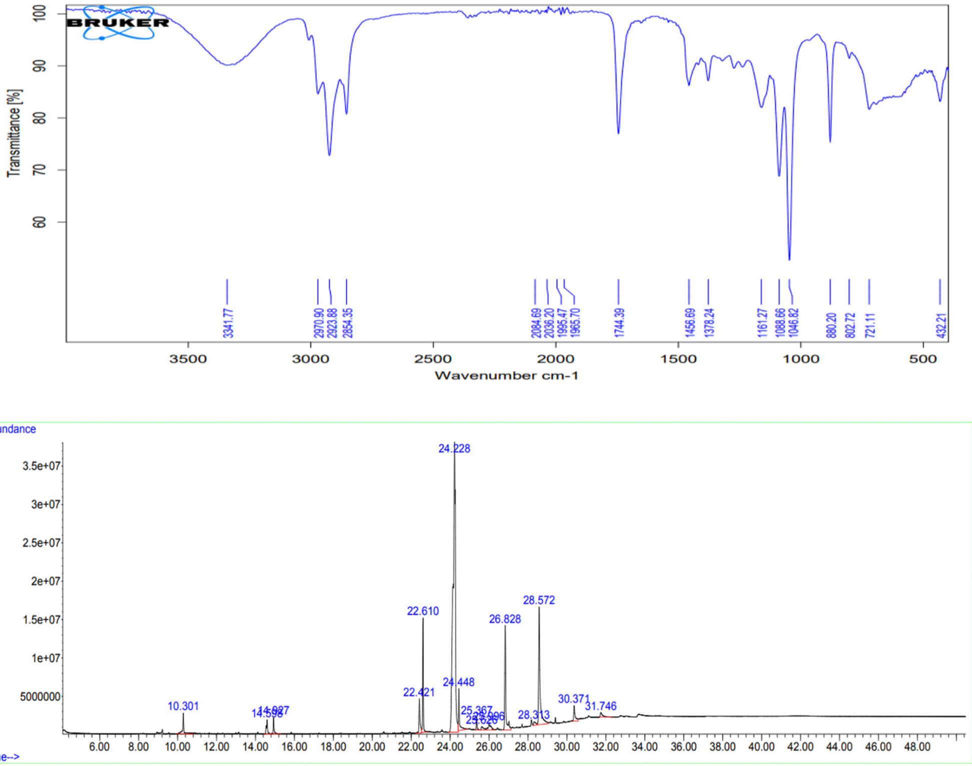

Figure 12. FT-IR spectra and GC-MS of biodiesel prepared by transesterification using $CaO\text{-}SiO_2$ catalyst

CONCLUSIONS

Oil extracted from the seeds of *Sisymbrium orientale* can be considered an important raw material in the production of biodiesel, as these seeds are renewable, readily available, inexpensive, and have a very good oil content, in addition to being unfit for human consumption. Biodiesel produced using KOH-catalyzed transesterification with $CaO\text{-}SiO_2$ met internationally recognized specifications. By studying the factors affecting the yield of the produced biodiesel, the optimum conditions were (ethanol: oil) ratio (6:1), reaction time of (1.5 hr.), catalyst amount of 1.5wt.%, and temperature of (60 °C) for the oil catalyzed with KOH, while for the catalyst using $CaO\text{-}SiO_2$, the optimum conditions were (ethanol: oil) ratio (6:1), reaction time of (1 hr.), catalyst amount of 1wt.%, and temperature of (60 °C). It achieves sustainable development goals by using vegetable oil and a catalyst prepared from food waste represented by eggshells and peanut shells.

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REFERENCE

1. Ameen, M., Zafar, M., Nizami, A., Ahmad, M., Munir, M., Sultane, S., Usma, A., Rehan, M. (2022). Biodiesel synthesis from *Cucumis melo* var. agrestis seed oil: Toward non-food biomass biorefineries. *Frontiers*, *10*, 830845. https://doi.org/10.3389/fenrg.2022.830845
2. Anastopoulos, G., Zannikou, Y., Stournas, S., Kalligeros, S. (2009). Transesterification of vegetable oils with ethanol and characterization of the key fuel properties of ethyl esters. *Energies*, *2*(2), 362–376. https://doi.org/10.3390/en20200362
3. Anekwe-Nwekeaku, O. J., Aniager, C. O., Osuji, L. C. (2025). Biodiesel production from selected seed oils: characterization, effect of process variables on biodiesel yield and engine performance testing. *Next Energy*, *8*, 100322. https://doi.org/10.1016/j.nxener.2025.100322
4. Bejene, D., Bekele, D., Abera, B. (2024). Biodiesel from blended microalgae and waste cooking oils: Optimization, characterization, and fuel quality studies. *AIMS Energy*, *12*(12), 408–43. https://doi:10.3934/energy.2024019
5. Bouaid, A., Iliuta, G., Marchetti, J. M. (2024). Cold Flow Properties of Biodiesel from Waste Cooking Oil and a New Improvement Method. *Heliyon*, *10*(17), e36756. https://doi.org/10.1016/j.heliyon.2024.e36756

6. Callegari, A., Bolognesi, S., Cecconet, D., Capodaglio, A. G. (2020). production technologies, current role, and future prospects of biofuels feedstocks: A state-of-the- art review. *Critical Reviews in Environmental Science Technology*, *50*(4), 384–436. https://doi.org/10.1080/10643389.2019.1629801
7. Cavalheiro, L. F., Rial, R. C., deFreitas, O. N., Domingues Nazario, C. E., Viana, L. H. (2021). Thermal Cracking of Fodder Radish (*Raphanus Sativus* L.) Oil to use as Biofuel. *Journal Analytical Applied Pyrolysis*, *157*, 105223. https://doi.org/10.1016/j.jaap.2021.105223
8. Changmai, B., Sudarsanam, P., Rokhum, L. (2020). Biodiesel production using a renewable mesoporous solid catalyst. *Ind. Crops. Prod, 145*, 111911. https://doi.org/10.1016/j.indcrop.2019.111911
9. Demirbas, A. (2009). Progress and recent trends in biodiesel fuels. *Energy Conversion* and *Management, 50*(1), 14–34. https://doi.org/10.1016/j.enconman.2008.09.001
10. Etim, A. O., Musonge, P., Eloka-Eboka, A. C. (2022). Process optimization of bio-alkaline catalysed transesterification of flax seed oil methyl ester. *Scientific African*, *16*, e01275. https://doi.org/10.1016/j.sciaf.2022.e01275
11. Fadhil, A. B. (2020). Production and characterization of liquid biofuels from locally available nonedible feedstocks. *Asia-Pacific Journal of Chemical Engineering*, *16*(15), e2572, 1–21. https://doi.org/10.1002/apj.2572
12. Fadhil, A. B., Abdulahad, W. S. (2014). Transesterification of mustard (*Brassica nigra*) seed oil with ethanol: Purification of the crude ethyl ester with activated carbon produced from de-oiled cake. *Energy Conversion and Management*, *77*, 495–503. http://dx.doi.org/10.1016/j.enconman.2013.10.008
13. Fadhil, A. B., Mohammed, H. M. (2018). Co-solvent transesterification of bitter almond oil into biodiesel: Optimization of variables and characterization of biodiesel. *Transport*. *33*(3), 686–698. https://doi.org/10.3846/16484142.2018.1457568
14. Fatah, M., Hamid, A., Rahmawati, Z., Purbaningtias, S. T. E., Jakfar, A. (2025). Synthesis of sodalite-natural dolomite as novel bifunctional catalyst for biodiesel production: experimental study of performance and emissions on diesel engine. *International Journal of Renewable Energy Development*, *14*(5), 1024–1035. https://doi.org/10.61435/ijred.2025.61434
15. Gardy, J., Rehan, M., Hassanpour, A., Lai, X., Nizami, A. S. (2019). Advances in nano-catalysts based biodiesel production from non-food feedstocks. *Journal of Environmental Management*, *249*, 109316. https://doi.org/10.1016/j.jenvman.2019.109316
16. Gupta, R., McRoberts, R., Yu, Z., Smith, C., Sloan, W., You, S. (2022). Life cycle assessment of biodiesel production from rapeseed oil: Influence of process parameters and scale. *Bioresource Technology*, *360*, 127532. https://doi.org/10.1016/j.biortech.2022.127532
17. Jamil, M. A. (2024). Production and optimization study of biodiesel produced from non-edible seed oil. *Science and Technology for Energy Transition*, *79*, 38. https://doi.org/10.2516/stet/2024036
18. Karmakar, B., Haldar, G. (2019). Progress and future of biodiesel synthesis: advancements in oil extraction and conversion technologies. *Energy Conversion and Management*, *182*, 307–339. https://doi.org/10.1016/j.enconman.2018.12.066
19. Khan, M. B., Kazim, A. H., Shabbir, A., Farooq, M., Farooq, H., Ali, Q., Danish, M. R., Qureshi, N. S., AbdulRab, H. (2020). Performance and emission of high purity biodiesel blends in diesel engine. *Advance Mechanical Engineering*, *12*(11), 1–10. https://doi.org/10.1177/1687814020974156
20. Kurczynski, D., Wcislo, G. (2024) Producing and testing the properties of biodiesel sourced from hemp oil. *Energies*, *17*, 5950. https://doi.org/10.3390/en17235950
21. Lauber, K., Wagner, G., Gygax, A. (2018). Flora Helvetica- Brassicaceae. Haupt Verlag, Berlin, Switzerland. 548. https://doi.org/10.5281/zenodo.10856934
22. Mahmood S. S., M. Al-Yaqoobi, A. (2024). Production of Biodiesel by using CaO Nano- catalyst Synthsis from Mango Leaves Extraction. *International Journal of Renewable Energy Development*, *13*(6), 1025–1034. https://doi.org/10.61435/ijred.2024.60469
23. Mahmood, H. A., Al-Sulttani, A. O., Alrazen, H. A., Attia, O. H. (2024). The impact of different compression ratios on emissions, and combustion characteristics of a biodiesel engine. *AIMS Energy*, *12*(5), 924–945. https://doi.10.3934/energy.2024043
24. Miladinovic, M. R., Zdujic, M. V., Veljovic, D. N., Krstic, J. B., Bankovic-Ilic, I. B., Veljkovic, V. B., Stamenkovic, O. S. (2020). Valorization of walnut shell ash as a catalyst for biodiesel production. *Renewable Energy*, *147*, 1033–1043. https://doi.org/10.1016/j.renene.2019.09.056
25. Mondal, J., Mizanur Rahman, A. N. M. (2024). Production and Characterization of Biodiesel from Linseed using NaOH Catalyst, Proceedings of the *14th International conference on Mechanical Engineering.* BUET, Dhaka, Bangladesh; http://dx.doi.org/10.2139/ssrn.4857814
26. Narayanan , M., Alshehri, M. A., Natarajan, A. (2024). Catalytic and thermochemical conversion of algal biomass to high-quality biofuel: A sustainable approach. *Journal of the Taiwan Institute of Chemical Engineers*. 105901. https://doi.org/10.1016/j.jtice.2024.105901

27. Nath, B., Kalita, P., Das, B., Basumatary, S. (2019). Highly efficient renewable heterogeneous bas catalyst derived from waste sesamum indicum plant for synthesis of biodiesel, *Renewable Energy*, *151*, 295-310. https://doi.org/10.1016/j.renene.2019.11.029
28. Nawaz, A., Abdur Razzak, S., Kumar, P. (2024). Pyrolysis parameter based optimization study using response surface methodology and machine learning for potato stalk. *Journal of the Taiwan Institute of Chemical Engineers*, *159*, 105476. https://doi.org/10.1016/j.jtice.2024.105476
29. Niyas, M. M., Shaija, A. (2022). Effect of repeated heating of coconut, sunflower, and palm oils on their fatty acid profiles, biodiesel properties and performance, combustion, and emission, characteristics of a diesel engine fueled with their biodiesel blends. *Fuel*, *328*, 125242. https://doi.org/10.1016/j.fuel.2022.125242
30. Ong, H. C., Silitonga, A. S., Masjuki, H. H., Mahlia, T. M. I., Chong, W. T., Boosroh, M. H. (2013). Production and Comparative Fuel Properties of Biodiesel from Non-edible Oils: *Jatropha Curcas*, *Sterculia Foetida* and *Ceiba Pentandra*. *Energy Conversion and Management*, *73*, 245–55. https://doi.org/10.1016/j.enconman.2013.04.011
31. Onukwuli, D. O., Emembolu, L. N., Ude, C. N., Aliozo, S. O., Menkiti, M. C. (2017). Optimization of biodiesel production from refined cotton seed oil and its characterization. *Egyptian Journal of Petroleum*, *26*(1), 103–110. https://doi.org/10.1016/j.ejpe.2016.02.001
32. Perveen, S., Hanif, M. A., Nadeem, R., Rashid, U., Azeem, M. W., Zubair, M., Nisar, N., Alharthi, F. A., Moser, B. R. (2021). A novel route of mixed catalysis for production of fatty acid methyl esters from potential seed oil sources. *Catalysts*, *11*(7), 811. https://doi.org/10.3390/catal11070811
33. Pradana, Y. S., Makertihartha, I. G. B. N., Indarto, A., Prakoso, T., Soerawidjaja, T. H. (2024). A review of biodiesel cold flow properties and its improvement methods: Towards sustainable biodiesel application. *Energies*, *17*(18), 4543. https://doi.org/10.3390/en17184543
34. Rahman, M., Khatun, A., Liu, L., Barkla, B. J. (2024). Brassicaceae mustards: Phytochemical constituents, pharmacological effects, and mechanisms of action against human disease. International Journal of Molecular Sciences, 25, 9039. https://doi.org/10.3390/ijms25169039
35. Razaq, Z., Touif, M. I., Noureen, S., Hussain, S. U., Saleem, M., Khan, F. M., Shaukat, U., Riaz, H., Zengin, G., Hashem, A., Kumar, A., Abd-Allah, E. F.(2024). Utilization of opium poppy seed oil for biodiesel production: A parametric characterization and statistical optimization. *Heliyon*, *10*, e36851. https://doi.org/10.1016/j.heliyon.2024.e36851
36. Razzaq, L., Farooq, M., Mujtaba, M. A., Sher, F., Farhan, M., Hassan, M. T., Soudagar, M. E. M., Atabani, A. E., Kalam, M. A., Imran, M. (2020). Modeling viscosity and density of ethanol-diesel-biodiesel ternary blends for sustainable environment. *Sustainability*, *12*(12), 5186. https://doi.org/10.3390/su12125186
37. Saeed, M. A., Farooq, M., Anwar, A., Abbas, M. M., Soudagar, M. E. M., Siddiqui, F. (2021). Flame propagation and burning characteristics of pulverized biomass for sustainable biofuel. *Biomass Conversion and Biorefinery*, *11*(2), 409–417. https://doi.org/10.1007/s13399-020-00875-y
38. Slani, H., Canakci, M. (2008). Effects of different alcohol and catalyst usage on biodiesel production from different vegetable oils. *Energy and Fuels*, *22*(4), 2712–2719.
39. Sovova, S., Abalymov, A., Pekar, M., Skirtach, A. G., Parakhonskiy, B. (2021). Calcium carbonate particles: synthesis, temperature and time influence on the size, shape, phase, and their impact on cell hydroxyapatite formation. *Journal Materials Chemistry B*, *9*, 8308–8320. https://doi.org/10.1039/D1TB01072G
40. Yazilitas, C., Yilbasi, Z., Yesilyurt, M. K. (2024). Biodiesel production from hempseed (*Cannabis sativa* L.) oil: Providing optimum conditions by response surface methodology. *Science and Technology for Energy Transition*, *79*, 11. https://doi.org/10.2516/stet/2024006