Materials Today Communications 39 (2024) 109128

Contents lists available at ScienceDirect

Materials Today Communications

journal homepage: www.elsevier.com/locate/mtcomm

Waste snail shells-derived mixed oxide catalyst for efficient transesterification of vegetable oil: Towards sustainable biodiesel production

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ARTICLE INFO

Keywords:
Transesterification
Biodiesel production
Mixed oxide catalyst
Soybean oil
Waste valorization

ABSTRACT

This study explores the transesterification process of soybean oil for the production of biodiesel, utilizing an innovative mixed oxide catalyst obtained from discarded snail shells powder. The catalyst synthesis involved a thermal treatment at 900°C for 120 min, predominantly yielding calcium oxide (CaO). In order to evaluate its properties, we carried out a thorough characterization using various analytical techniques. The study explores the impact of crucial variables on the transesterification reaction, such as reaction time (from 30 to 150 min), methanol-to-oil ratio (from 3:1–18:1), and catalyst concentration (from 0.5 % to 4 % by weight). Optimal conditions emerged with a 90-min reaction time, a 12:1 methanol-to-oil ratio, and a 2 % catalyst loading, yielding an impressive biodiesel conversion rate of approximately 93 %. The validity of biodiesel conversion was confirmed through Fourier transform infrared spectroscopy (FTIR) and Proton Nuclear Magnetic Resonance Spectroscopy (1 H NMR). The resultant biodiesel exhibited highly favorable characteristics, including an acid value of 0.85 mg of KOH/g, a density of 886.8 kg/m3, and a viscosity of 4.6 mm^2/s. These measurements align with the standards set forth in EN 14214 and ASTM D6751 regarding biodiesel quality. The utilization of waste snail shells powder as a precursor for synthesizing the mixed oxide catalyst presents a promising approach for the sustainable production of biodiesel from soybean oil, offering a sustainable and efficient approach to biofuel production.

1. Introduction

As the demand for renewable fuels intensifies due to environmental concerns, biodiesel production has garnered significant attention. However, current methods often depend on resource-intensive feedstock or expensive metal-based catalysts, prompting the exploration of sustainable and cost-effective alternatives. Biodiesel is a sustainable alternative fuel for diesel engines, offering reduced energy consumption, decreased reliance on fossil fuels, and improved air quality. Additionally, its high flash point, good lubricity, and biodegradability make it safer and less harmful to the environment than petroleum diesel [2,30].

Although biodiesel production from vegetable oils has gained attention for its potential to reduce dependence on fossil fuels and address environmental concerns, the predominant use of conventional feedstocks raises concerns about competition with food production. To address this challenge, there's growing interest in exploring alternative feedstocks, including seed oil [12], sugarcane bagasse [5], quinary oil [8], Musa glauca [24,32] and mixed oils [7]. Generally, any material that contains triglycerides can be used to produce biodiesel. Blended feedstocks, combining various sources, offer advantages like increased resource efficiency, reduced competition with food crops, and improved cold flow properties of the final biodiesel product. While this study focuses on utilizing soybean oil for biodiesel production with a novel snail shell catalyst, the potential for exploring waste or non-edible feedstocks

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https://doi.org/10.1016/j.mtcomm.2024.109128
Received 22 February 2024; Received in revised form 20 March 2024; Accepted 3 May 2024
Available online 6 May 2024
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in future research is acknowledged.

Transesterification is the process of combining oil, alcohol, and catalyst in order to produce a sustainable fuel predominantly composed of fatty acid methyl ester (FAME) [27]. Optimizing reaction parameters is an important aspect of biodiesel production since it has a significant impact on both yield and final product quality. The choice of reactants, catalysts, reaction time, temperature, and mixing ratios all play critical roles in determining the efficiency of the transesterification process [11].

Heterogeneous catalysts, reusable solid catalysts, play a vital role in biodiesel production by accelerating the transesterification reaction. Various types of heterogeneous catalysts have been explored for this purpose, including solid acid catalysts like ion-exchange resins and zeolites, solid base catalysts such as alkali metal oxides, and even enzymes like lipases [9,34]. Metal oxide-based catalysts represent a promising class of heterogeneous catalysts due to their affordability, low toxicity, high basicity, and excellent transesterification activity. Researchers have shown interest in synthesizing catalysts from biogenic $CaCO_3$ materials such as eggshells, snail shells, animal bones and sea shells, making the biodiesel production process more cost-effective and environmentally sustainable [4,8,14,25]. The mixture of oxide phases gives useful functions and features that improve the material's catalytic activity [20]. Various mixed metal oxides have been employed in biodiesel processing, including CaO/ZnO [31], K_2O/ K_2CO_3 [5], CaO-Al_2O_3, CaO-La_2O_3 and CaO-ZnO [10,28] and Metal- Organic Framework (MOF) [6,16].

This study introduces a novel approach to biodiesel production by investigating the utilization of a mixed oxide heterogeneous catalyst derived from snail shell powder. This catalyst offers a cost-effective and environmentally sustainable alternative to conventional ones. The primary objective of this research is to assess the efficacy of the snail shell catalyst in catalyzing the transesterification of soybean oil. Specifically, the study aims to optimize reaction parameters such as catalyst loading, reaction time, and temperature to maximize biodiesel yield while minimizing resource consumption and environmental impact. Additionally, the investigation seeks to characterize the chemical changes occurring during the transesterification process using FTIR analysis, providing insights into the structural modifications in both the starting material (soybean oil) and the resulting biodiesel. Through these objectives, the study aims to contribute to the advancement of sustainable biodiesel production methods while addressing the need for alternative catalysts and feedstocks in the renewable energy sector.

2. Materials and methods

2.1. Materials

Soybean oil (S-OIL) was obtained from a local market in Fez, Morocco, serving as the primary vegetable oil source for this study. Phenolphthalein indicator, methanol (purity: 99.8 %), and sodium hydroxide (purity: 98 %) were sourced from Sigma Aldrich. Throughout the research, analytical-grade chemicals, reagents, and solvents were utilized to ensure consistency and accuracy in the experimental procedures.

2.2. Catalyst preparation

The catalyst derived from snail shell (CWSS) was synthesised from the residual material remaining after the copper Cu(II) removal by snail shells powder (SSP) [29]. Fig. 1 showed the preparation method. For this purpose, the Residual SSP was calcined at 900 °C in an air atmosphere for 120 min. A Nabertherm P330 muffle furnace was used to carry out the thermal treatment.



Fig. 1. Preparation of CWSS derived from Residual SSP.

2.3. Characterization

2.3.1. Fourier transform infrared spectroscopy

FTIR was measured with a Bruker Vertex 70 spectrometer. The analysis was performed in attenuated total reflectance (ATR) mode, with a wavenumber range of 400–4000 cm^{-1}, 16 scans, and a resolution of 4 cm^{-1}.

2.3.2. Scanning electron microscopy

Scanning electron microscopy (SEM) analysis of the sample was conducted with a JEOL JSM-IT500HR microscope equipped with an energy-dispersive X-ray spectroscopy (EDS) system, which allows for the elemental analysis of samples. The SEM was operated in high-vacuum mode at a working distance of 11.9 mm.

2.3.3. X-ray diffraction

X-ray diffraction (XRD) analysis was performed using a Panalytical X'Pert Pro X-ray diffractometer, equipped with a Cu-Kα monochromatic source (wavelength of 1.54 Å), operating at a filament current of 40 mA and a voltage of 40 kV. The analysis was conducted through continuous scanning with a step size of 0.017° (2θ) and a scan step time of 45 s. The XRD patterns were recorded over a 2θ angle range of 10° to 90° and subsequently analyzed using Panalytical HighScore software.

2.3.4. Nuclear magnetic resonance spectroscopy

^1H NMR was performed using a Bruker Avance-300 spectrometer using a 5 mm NMR tubes Wilmad ® at ambient temperature. The samples were dissolved in deuterated chloroform ($CDCl_3$). ^1H NMR spectra of samples were processed in the software TopSpin 3.2.

2.3.5. Transesterification reaction

The transesterification reaction was carried out in a 250 mL flat-bottom reactor flask equipped with three necks and featuring a magnetic stirrer bar coated with polytetrafluoroethylene (PTFE), a reflux condenser, and a digital thermometer. The reactor was placed on a hot plate magnetic stirrer to maintain a stable temperature.

A predetermined amount of synthesized CWSS catalyst was added to the calculated quantity of methanol and stirred to promote the formation of methoxide. Subsequently, 50 g of S-OIL was introduced into the flask reactor and heated to 60°C. Afterward, the CWSS in methanol solution was added. The stirrer speed was kept constant at 1000 rpm and the temperature was maintained at 60°C throughout the reaction process. To ensure reproducibility, triple replicates of each experiment were conducted.

After the reaction was complete, two layers formed. The lower layer, containing glycerol and catalyst, was discarded, while the upper layer, consisting primarily of methyl esters (biodiesel), was purified. The biodiesel underwent a washing process using warm distilled water to effectively eliminate undesirable byproducts, including any residual soap, unreacted methanol, and lingering traces of glycerol that might persist in the biodiesel.

After washing, the biodiesel was further purified by heating it in an oven at 100°C for 3 h to remove any remaining traces of water and methanol. The obtained biodiesel was weighed and stored for subsequent assessment. Fig. 2 shows a schematic workflow for the synthesis of biodiesel using S-OIL.

A series of experiments were carried out to investigate the effect of

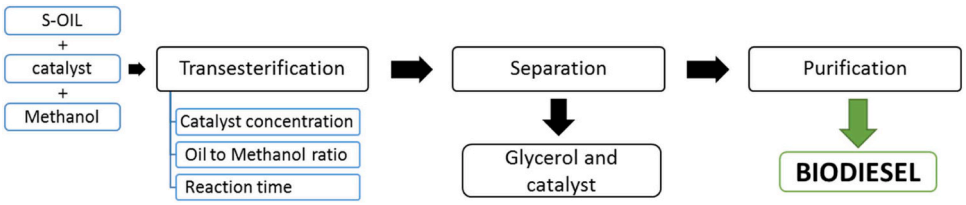


Fig. 2. Overall scheme of biodiesel production from S-OIL.

three experimental factors on the transesterification reaction: reaction time (30–150 min), methanol to oil ratio (3:1–18:1), and catalyst loading (0.5–4 wt %).

2.3.6. Fatty acid methyl ester analysis

The performance of the transesterification reaction was evaluated by measuring the biodiesel yield as a percentage of the total mass. The biodiesel yield ($Yield_{weight}$ (%)) was calculated by measuring the mass of the biodiesel ($m_{biodiesel}$) and the mass of S-OIL (m_{oil}) using the flowing equation [27]:

$$Yield_{weight}(\%) = \frac{m_{biodiesel} \times 100}{m_{oil}} \quad (1)$$

2.3.7. Acid value

The Acid Value (AV) is a crucial parameter used to measure the acidity of a substance, specifically the number of milligrams of potassium hydroxide (KOH) necessary to neutralize the fatty acids within a one-gram sample.The determination of Acid Value is typically achieved through an acid-base titration method, adapted from the NF EN ISO 660 standard [18].

A 2 g sample was placed in a flask, to which 10 mL of a 1:1 (v/v) mixture of ethanol/diethyl ether or toluene was added, along with 2–3 drops of a 1 % phenolphthalein indicator solution.

The sample is subsequently titrated with a 0.1 N potassium hydroxide solution. As the free fatty acids are neutralized, the solution changes to a pink color. The volume of KOH used was employed to calculate the AV using the flowing equation:

$$AV = \frac{M_{KOH} \times V_{KOH} \times C_{KOH}}{m_{oil}} \quad (2)$$

Where M_{KOH} represents the molar mass of KOH (56.1 $g.mol^{-1}$), V_{KOH} is the volume of the KOH solution used (in mL), C_{KOH} denotes the concentration of the KOH solution (in $mol.L^{-1}$), and m_{oil} is the mass of the test sample (in g).

2.3.8. Density

The density of the sample was determined through a pycnometer previously calibrated with deionized water at 20°C. For this purpose, a dry pycnometer was filled with distilled water before being measured with an electronic balance. Subsequently, the weight of pycnometer filled with the sample was also weighed. The specific gravity value was calculated using the following formula [26]:

$$\text{Specific gravity(unit less)} = \frac{\text{sample weight(g)}}{\text{distilled water weight(g)}} \quad (3)$$

The density of the sample was thereby determined using:

$$\rho_{Sample} = \text{Specific gravity} \times 1 g.cm^{-3} \quad (4)$$

2.3.9. Kinematic viscosity

The viscosity was determined using a capillary kinematic viscometer (Fig. 3) immersed in a bath at 20 °C constant temperature. The determination of viscosity consists of measuring the time that a fixed volume of sample takes to flow through the capillary of the viscometer under the action of gravity. The kinematic viscosity is the product of time and the calibration constant of the viscometer. It is calculated using the flowing equation:

$$\nu = c \times t \quad (5)$$

Where:

c = viscometer calibration constant (2234.10^2 $mm^2.s^{-2}$)

t = time, in seconds, that the sample takes to cover distance between the start and the end marking of the viscometer.

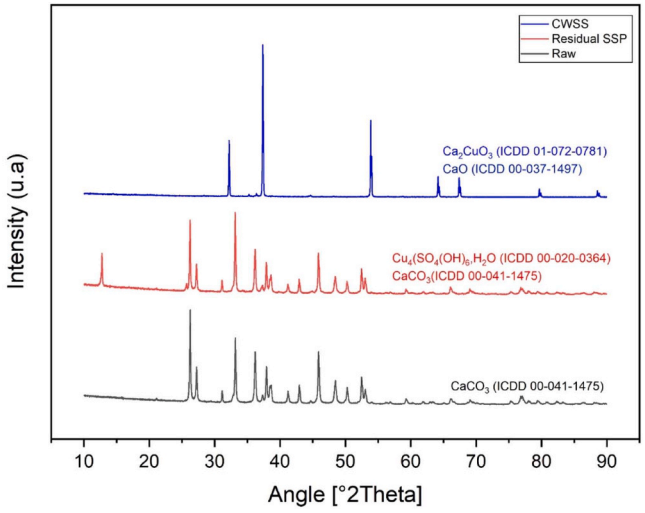


Fig. 3. XRD spectrum of CWSS catalyst, residual SSP and Raw SSP.

3. Results and discussion

3.1. Characterization of CWSS catalyst

3.1.1. XRD analysis

Fig. 3 shows the XRD pattern of the synthesized CWSS. The peaks perceived at 32.21°, 37.36°, 53.88°, 64.18°, 67.40°, 79.69° and 88.57° correspond to the presence of cubic calcium oxide (CaO) as the main phase in agreement with the reported diffraction peaks (ICDD reference code 00–037–1497). Minor phase of calcium copper oxide (Ca_2CuO_3) was also observed (ICDD reference code 01–072–0781). The CWSS catalyst is indeed a composite of metal oxides, comprising both CaO and Ca_2CuO.

The crystalline nature of the CWSS was shown by the XRD pattern's strong and distinct peaks. These findings align with those reported by Ha et al. [17] in their paper.

The XRD pattern of residual SSP revealed the presence of monoclinic posnjakite [$Cu_4(SO_4)$ $(OH)_6$,H_2O] (ICDD reference code 00–020–0364). Posnjakite is classified within the same mineral group as langite and wroewolfeite.

3.1.2. SEM analysis

As demonstrated in Fig. 4(a), the CWSS catalyst's surface morphology revealed spherical aggregated particles dispersed

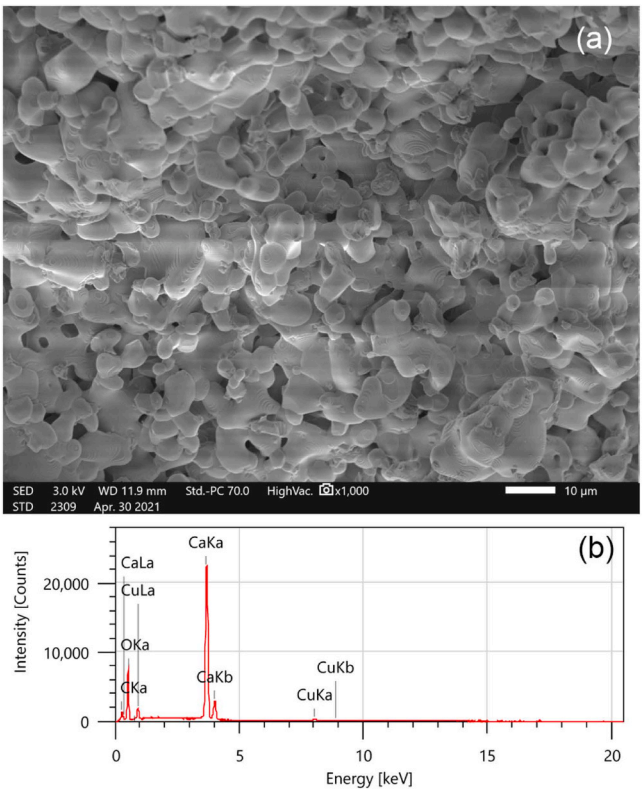


Fig. 4. Characterization of CWSS: (a) SEM images; (b) EDS spectrum.

throughout the catalyst surface.

Most notably, the image exposed the presence of a porous structure. Such porosity in a catalyst significantly augments its surface area, thereby amplifying its catalytic activity. Fig. 4(b) presents the results of EDS analysis, shedding further light on the catalyst's composition, which prominently featured calcium and oxygen, with a comparatively lower concentration of copper.

Lee et al. observed the morphology of CaO-MgO and CaO-ZnO using SEM images. The catalysts showed large aggregated particles on their surface [20]. Baskar et al. observed that ZnO nanocatalyst was spherical in shape and cluster in the form [3].

3.2. Effect of reaction parameters

3.2.1. Effect of reaction time

In the study, the influence of reaction time on biodiesel yield, as illustrated in Fig. 5, was systematically investigated within a time frame spanning from 30 min to 150 min. The experimental conditions were rigorously controlled, featuring a consistent methanol-to-oil molar ratio of 6:1 and a catalyst concentration of 1 wt %. The reaction temperature was held constant at 60°C, providing a stable environment for the transesterification process, while the stirring speed was maintained at 1000 rpm to ensure effective mixing and uniformity. This methodical investigation allowed for a comprehensive evaluation of the impact of varying reaction times on biodiesel production, shedding light on the optimal time frame for achieving maximum yields while maintaining the specified reaction parameters.

The findings showed a progressive rise in yield over time, peaking at approximately 73 % after 90 min. However, the yield experienced a slight decline beyond this point due to the potential onset of ester hydrolysis, resulting in increased formation of fatty acids and soap. Furthermore, due to the reversible nature of the reaction, there is a possibility of a reverse reaction taking place once equilibrium is attained, which can ultimately reduce the overall yield.

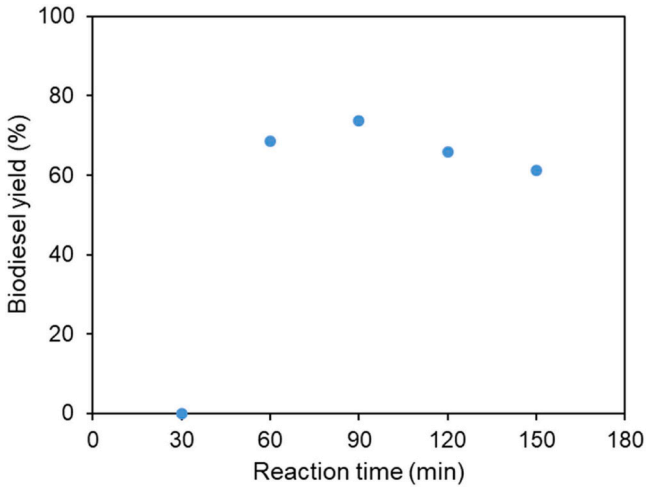


Fig. 5. The effect of reaction time on the biodiesel yield.

3.2.2. Effect of methanol to oil ratio

The influence of the methanol-to-oil molar ratio on biodiesel yield depicted in Fig. 6 was carried out across a range spanning from 3:1–18:1. Throughout the experimental process, a fixed catalyst concentration of 1 wt % was maintained. The reaction was permitted to proceed for a duration of 90 min, operating under controlled conditions at a consistent temperature of 60°C and a stirring speed of 1000 rpm.

Biodiesel production involves a complex chemical transformation, specifically the transesterification of triglycerides derived from sources such as S-OIL. This process entails the use of methanol in the presence of a catalyst like CWSS, which facilitates the conversion of triglycerides into three lower molecular weight methyl esters. Simultaneously, glycerol is released as a by-product of the reaction. The stoichiometry of this transesterification reaction adheres to a one-to-three ratio, mandating one mole of triglyceride to react with three moles of methanol. Fig. 7 represents the general reaction scheme. To drive the reaction towards the production of methyl esters, which are key components of biodiesel, an excess of methanol is employed. This approach accounts for the reversible nature of the transesterification reaction and plays a pivotal role in promoting the efficient formation of biodiesel.

As shown In Fig. 6, an enhancement in the biodiesel yield was observed as the molar ratio increased from 3:1–12:1. A maximum yield of approximately 84 % was achieved at a molar ratio of 12:1. The rise in methanol quantity facilitates the generation of methoxy species on the surface of CWSS, promoting the formation of methyl esters by shifting

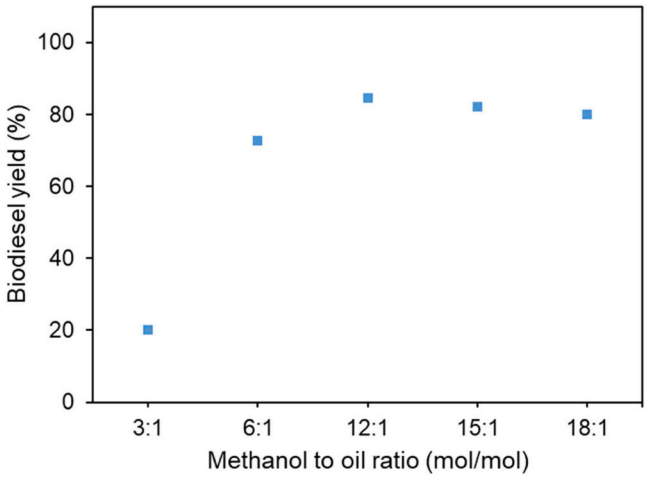


Fig. 6. The effect of methanol to oil ratio on the biodiesel yield.

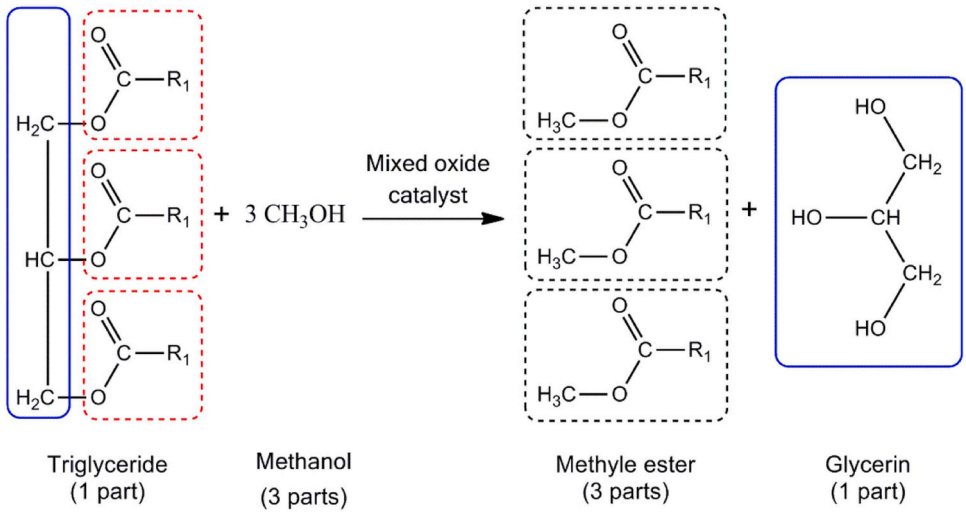


Fig. 7. The general reaction of biodiesel synthesis with the CWSS.

the reaction equilibrium. However, further increasing the molar ratio beyond 12:1 causes a slight drop in biodiesel yield. This can be attributed to the excess methanol dissolving the glycerol, leading to the possibility of a back reaction that hinders the interaction between methanol, CWSS, and S-OIL. Numerous studies have shown that the oil-to-methanol molar ratio has a substantial influence on biodiesel yield [21,22,33].

3.2.3. *Effect of catalyst concentration*

In the pursuit of optimizing biodiesel production, the influence of catalyst concentration was meticulously investigated within a range spanning from 0.5 to 4 wt % CWSS, based on the S-OIL substrate. Throughout the course of the experiment, a constant methanol-to-oil molar ratio of 12:1 was maintained to ensure a consistent reaction environment. The reaction itself was allowed to proceed for a duration of 90 min, holding a steady temperature of 60°C and a stirring speed of 1000 rpm.

The results of these systematic variations in catalyst concentration are thoughtfully presented in Fig. 8. By scrutinizing the results, this study aims to unravel the intricate relationship between catalyst concentration and biodiesel yield, providing valuable insights into optimizing biodiesel synthesis processes.

During the transesterification process, CWSS's active sites facilitate the conversion of methanol into highly reactive methoxide ions. These methoxide ions then target the carbonyl carbon in glyceride molecules, forming biodiesel. When the catalyst concentration is increased, it augments the total number of active sites, thus facilitating a more extensive conversion of biodiesel. A prior study by Lee et al. [20] documented the emergence of methoxide species on the surface of mixed metal oxide catalysts, which enhances the transesterification reaction. This enhancement is attributed to the presence of highly electronegative oxide phases within the catalyst, creating strong basic sites within the active site. These basic sites effectively break the (O-H) bonds in methanol, yielding hydrogen cations and methoxide anions [20].

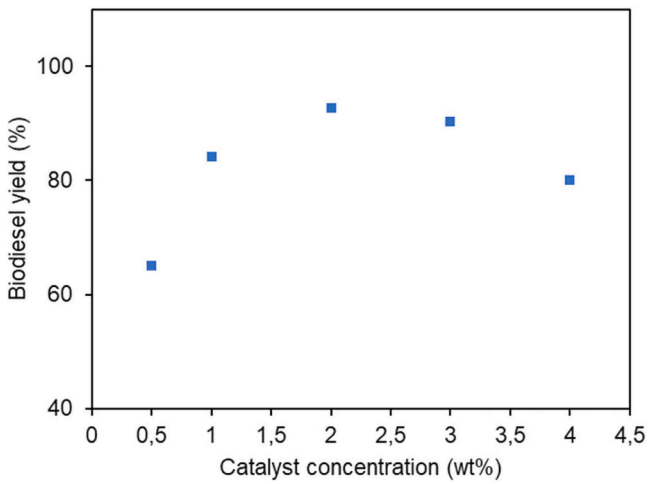


Fig. 8. The effect of CWSS concentration on the biodiesel yield.

The highest biodiesel yield, reaching approximately 93 %, was noticed at a catalyst concentration of 2 wt %. Nonetheless, with a higher catalyst concentration, the biodiesel yield exhibited a declining trend. This decline can be attributed to the heightened viscosity of the reaction mixture due to an excessive amount of catalyst. The elevated viscosity impedes the diffusion of reactants and limits their interaction with the catalyst, ultimately leading to reduced biodiesel production.

3.3. *Transesterification mechanism*

The mechanism of the catalyst in transesterification reactions, with a focus on the major active phase CaO in CWSS, is depicted in Fig. 9. The breakdown of the triglyceride molecule occurs in four distinct steps.

In the initial phase, a reaction occurs between calcium oxide and methanol, leading to the formation of a critical species known as the methoxide anion. This anion serves as a pivotal catalyst for the subsequent reactions. Moving to the second step, the methoxide anion actively attacks the carbonyl carbon within the triglyceride molecule, giving rise to the creation of an alkoxycarbonyl intermediate structure. In the third stage, this alkoxycarbonyl intermediate acquires a hydrogen proton, derived from CaO-H+, resulting in the production of calcium oxide and another alkoxycarbonyl intermediate. The fourth step involves a series of rearrangements and cleavage reactions, ultimately yielding the fatty acid methyl ester, commonly referred to as biodiesel. Simultaneously, this process generates diglyceride as a co-product. These intricate chemical transformations, orchestrated by the involvement of catalysts and intermediates, constitute the foundation of biodiesel production.

As the transformation progresses, both diglyceride and monoglyceride undergo similar reactions, ultimately producing glycerin and biodiesel.

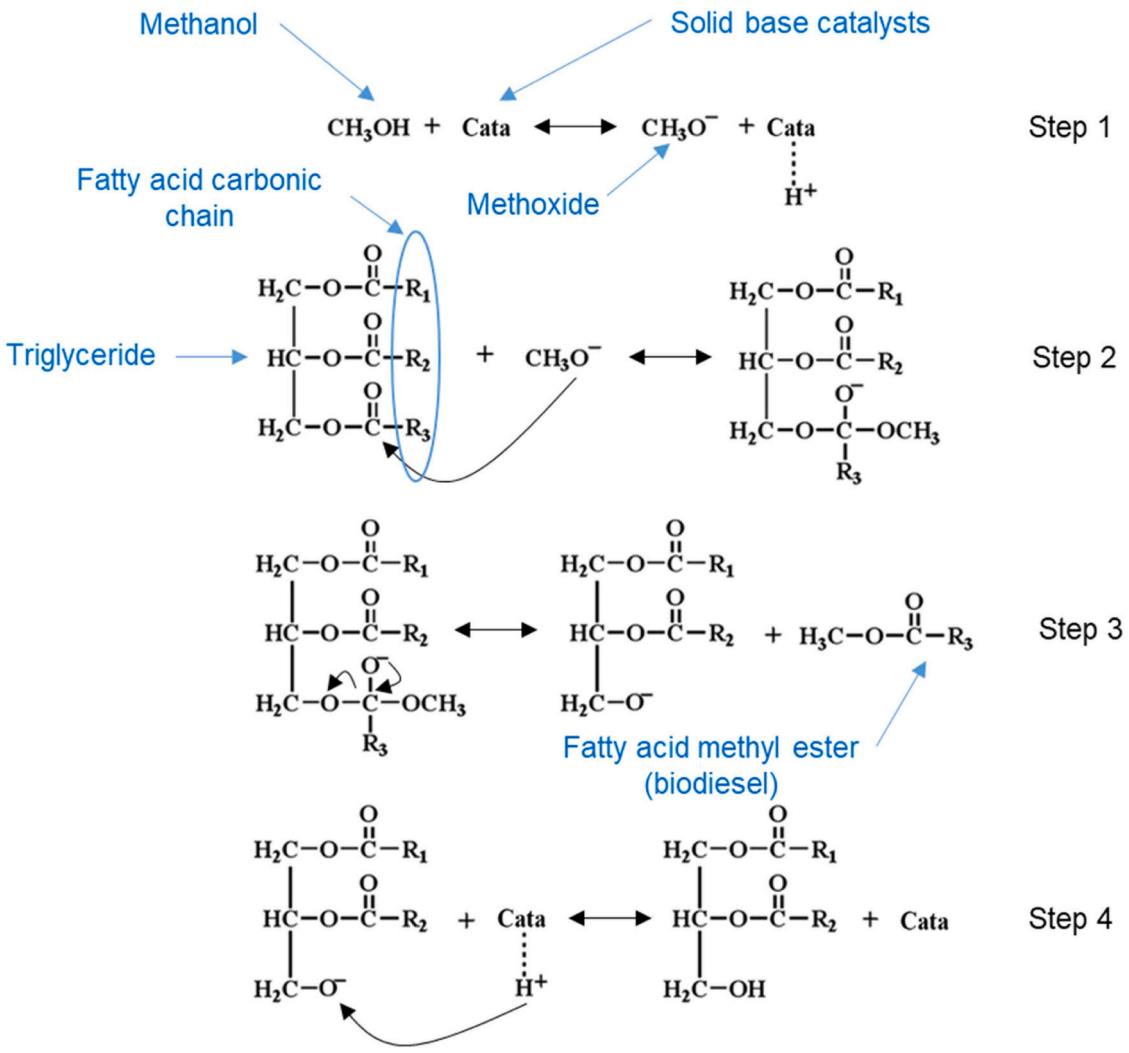


Fig. 9. Mechanism of transesterification of triglyceride with methanol and CWSS.

3.4. Characterization of biodiesel obtained by transesterification

3.4.1. FTIR analysis of biodiesel

The FTIR spectroscopy was used to examine the functional groups in both biodiesel and S-OIL samples. The spectroscopic analysis, as illustrated in Fig. 10, revealed a striking chemical similarity between the FTIR spectra of biodiesel and S-OIL, with slight differences. Notably, the most significant change in the oil structure was the substitution of glycerol with methanol in the hydrocarbon chain. Consequently, the FTIR spectrum of biodiesel displayed strong resemblance to triglyceride, with the main deviations observed within the 1000–1600 cm^{-1} range.

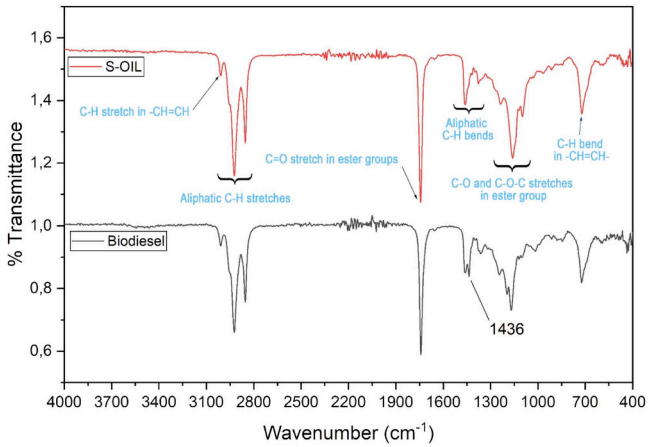


Fig. 10. FTIR spectrum of biodiesel compared with S-OIL.

The FTIR spectrum exhibited notable features, including strong bands associated with aliphatic -C-H stretching vibrations within the range of 2800–2980 cm^{-1}, as well as -C-H bending vibrations in the region of 1410–1490 cm^{-1}. Furthermore, the absorption bands at 3008 cm^{-1} and 725 cm^{-1} were attributed to stretching of C-H bonds and bending of C-H bonds, respectively.

Within the spectral region between 1010 and 1300 cm^{-1}, an absorption band was observed, corresponding to the stretching vibrations of –C–O and C-O-C groups. Notably, peaks within the 1800–1700 cm^{-1} range, assigned to C═O stretching, were detected in both biodiesel and S-OIL spectra, affirming the ester nature of the samples.

However, biodiesel can be distinguished from S-OIL using FTIR spectra in the region 1500–900 cm^{-1}. In particular, the presence of an absorbance band at 1436 cm^{-1}, corresponding to the asymmetric stretching of O–CH_3, confirmed the formation of biodiesel. This specific band was conspicuously absent in the S-OIL spectrum. Prior research has also identified similar FTIR bands in biodiesel, further corroborating these findings [3,19,23].

3.4.2. NMR analysis of biodiesel

The ^{1}H NMR spectrum of biodiesel with chemical shift assignments, shown in Fig. 11, revealed the presence of a pronounced singlet at 3.560 ppm characteristic of the protons of the methoxy groups (indicated by the letter A). The signal obtained as a triplet at 2.208 ppm is attributed to the α-carbonyl groups of methylene (indicated by the letter B) present in all derivatives of triglycerides of S-OIL oil as well as in biodiesel.

The emergence of the distinctive peak related to methoxy protons (-O-CH_3) serves as confirmation that the conversion of S-OIL into biodiesel occurred during the transesterification process with CWSS. These results align with the findings reported by Laskar et al. [19] and Doudin [13].

3.4.3. Physico-chemical characterization of biodiesel

Table 1 provides a comparison of the characteristics of S-OIL and biodiesel produced through transesterification using CWSS with the specifications outlined in EN 14214:2008 and ASTM D6751.

The S-OIL vegetable oil used in this study has a high viscosity of approximately 31.84 mm^2/s, making it inappropriate for direct use in engines. However, through the process of transesterification, the oil can be converted into esters with lower viscosity that meet the technical requirements of diesel engines. This reduction in viscosity is attributed to the breakdown of triglycerides present in S-OIL [1,15].

Following the transesterification reaction, significant improvements were observed in the characteristics of the S-OIL oil. The acid value, density, and viscosity were notably reduced from 1.25 to 0.48 mg KOH/g, 926.8–887.1 kg/m^3, and 31.84–4.26 mm^2/s, respectively.The biodiesel produced demonstrated favorable results in terms of density, viscosity, and acid value, aligning with the recommended standards of ASTM D6751 and EN 14214. This achievement confirms that the produced biodiesel meets the necessary quality criteria outlined by these established standards.

Table 1
Physicochemical characteristics of S-OIL oil and the biodiesel produced compared to the European (EN 14214) and American (ASTM D6751) standard for biodiesel.

Caractéristiques	S-OIL	Biodiesel	Europe EN 14214	USA ASTM D6751
Acid value (mg KOH/g)	1,25 ±0,10	0,48±0,09	<0.5	<0.5
Density (kg/m^3)	926,80 ±3,52	887,17 ±2,21	860–900	-
Kinematic viscosity at 40 °C (mm^2/s)	31,84 ±0,71	4,26±0,10	3.5-.5.0	2.0–4.5

4. Conclusion

The study investigates the potential of a catalyst derived from snail shell powder, initially employed for copper removal, in the transesterification process to produce biodiesel from S-OIL. After calcination at 900°C, the catalyst predominantly consisted of highly crystalline CaO, with minor Ca_2CuO_3, confirmed by XRD analysis. Employing a reaction time of 60 min, methanol to oil ratio of 12:1, and catalyst loading of 2 wt %, yielded a biodiesel conversion of approximately 92.3 %. Biodiesel conversion was validated by FTIR and 1 H NMR spectroscopy. Post-reaction, S-OIL's acid value, density, and viscosity significantly decreased, meeting EN 14214 and ASTM D6751 standards. Utilizing snail shell powder for biodiesel production catalysts offers novel eco-friendly alternatives, contributing to sustainable biodiesel production and environmental preservation.

CRediT authorship contribution statement

Redouane Ouafi: Formal analysis, Conceptualization, Investigation. **Rajesh Haldhar:** Validation, Writing – original draft. **Zakia Rais:** Writing – review & editing. **Mustapha Taleb:** Validation. **Seong Cheol Kim:** Supervision. **Imane Mehdaoui:** Methodology. **Meryem Asri:** Data

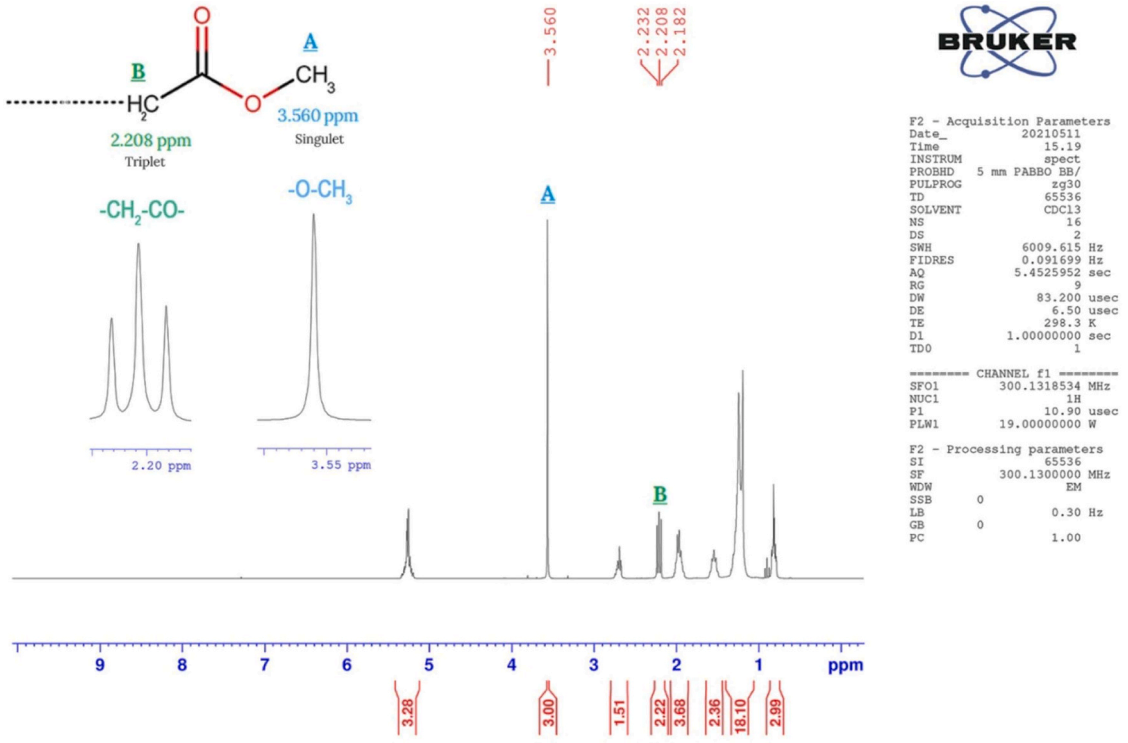


Fig. 11. ^{1}H NMR spectroscopy of biodiesel with assignments of chemical shifts of protons of methoxy groups indicated by the letter A (3.560 ppm, strong singlet) and those α-carbonyl methylene groups indicated by the letter B existing in all triglyceride derivatives of the S-OIL as well as in biodiesel (2.208 ppm, triplet).

curation. **Ismail Warad:** Data curation. **Abeer A. AlObaid:** Writing – original draft, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

The authors extend their appreciation to the Researchers Supporting Project number (RSP2024R381), King Saud University, Riyadh, Saudi Arabia. Also, this research was supported by the NRF (National Research Foundation) of Korea funded by the Basic Science Research Program through the Ministry of Education (2020R1I1A3052258).

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