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Transesterification of Refined Waste Cooking Oil Using SrO-KF Catalyst Under Ultrasonic Wave

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Waste cooking oil is a potential raw material for biodiesel. The use of heterogeneous catalysts and ultrasonicator will optimize the transesterification and environmentally friendly. The transesterification study with SrO-KF nano catalyst has been carried out. The objectives of this study are: (1) to determine the optimum conditions for SrO-KF catalyst in the synthesis of biodiesel of the refined waste cooking oil and (2) to compare the results of the methyl ester with biodiesel standards. The steps of this study were: refinement of waste cooking oil, synthesis of SrO-KF nano-catalyst, and the transesterification. The catalyst applied ratio of 1:1, 1:2, and 1:3 of SrO:KF with concentrations of 2%, 3% and 4% by weight of oil respectively. The results of heterogeneous catalyst using XRD and SEM showed that SrF₂, SrO and KF compounds had been formed. The optimum transesterification conditions were obtained on SrO-KF catalyst (1:2), concentration of 4% (w/w) with a yield of 85.12% (w/w). The methyl ester of waste cooking oil has density of 884 kg/m³, acid number of 0.48 mg/g, and viscosity of 4.2 cSt. Methyl esters of waste cooking oil were composed of 25.14% methyl palmitate and 33.65% methyl elaidate, 11.27% methyl linoleate, 10.14% methyl lauric and other methyl esters.

Graphical abstract



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1. Introduction

The consumption of diesel fuel has endangered the environment. Biodiesel is an alternative fuel to substitute diesel. In the world, biodiesel production is projected from

48.3 billion liters (2021) to 49.9 billion liters (2030) [1]. This reflected the demand of biodiesel fuel. As environmentally friendly fuel. The properties of biodiesel are influenced by

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chemical composition, fatty acid components, and oil raw materials [2]. One of the promising alternative raw materials of biodiesel is waste cooking oil. Waste cooking oil has characteristics such as brownish in color, thick, foamy, an unpleasant smell [3]. Consumption of waste cooking oil-fried food can cause carcinogenic effects to the human body [4]. On the other hand, the disposal of high loads of waste cooking oil can cause environmental problems, especially water and soil pollutions [5]. Unfortunately, waste cooking oil is resulted from palm-cooking oil that has a high abundance. For example, palm oil production was 54.5 million tonnes in 2020 and increase to over 78 million tonnes in 2045 [6]. So, waste cooking oil production can be reduced by utilizing it as raw material for biodiesel which the characteristics of waste cooking oil are similar to palm oil, especially free fatty acids and triglycerides.

Waste cooking oil need to be refining process first to remove impurities, minimize unpleasant odors, and make the oil appear clearer [7]. Adsorption method is a well-known method of refining process reported. Adsorption by clay minerals has many advantages, i.e.: effective removing of grease and dirt, abundant availability, and low price [8]. In this work, bentonite as one of clay minerals has high silica content, easy ability, cheap price, as it is a potential to be used in the refinement process [8].

After refining, the initial method of synthesizing biodiesel was to reduce the content of free fatty acids (FFA) to below 1% content [9]. Alkaline catalyst can react with FFA to form soap, which will complicate purification, reduce biodiesel yield and increase consumption of catalyst and methanol [10]. Therefore, lowering FFA is necessary in this work, by esterification process [11].

Waste cooking oil with < 2% of FFA level can be carried out by transesterification [12]. In transesterification reaction, methyl ester compounds as Biodiesel produced by reactions of waste cooking oil (as triglycerides) with alkoxide ions in methanol [13]. Several factors affect the transesterification reaction, i.e: reaction time, temperature, type of catalyst and the molar ratio of the oil and alcohol [14]. The transesterification of waste cooking oil and alcohol generally uses a homogeneous base catalyst. However, homogeneous catalysts also have disadvantages, such as difficulty in product separation, requiring large amounts of water, and environmental pollution [15]. A new trend in the synthesizing of biodiesel is to use a more environmentally friendly method based on solid base heterogeneous catalyst, especially bifunctional catalyst [16].

Solid base heterogeneous catalysts derived from the alkaline earth metal group have advantages such as high activity, long catalyst life, environmentally friendly, little waste, and easy reusability [17]. One of the alkaline earth metal group is strontium oxide (SrO). The SrO catalyst has attracted to

explore because of its high basicity and its insolubility in mixtures of transesterification process [18]. The results of the transesterification of waste cooking oil using 0.1% of SrO catalyst produced a biodiesel yield of 48.2% in conditions: methanol/oil molar ratios (9:1), 60 °C for 2 h [19]. However, SrO has a low surface area of and leaching occurs during the process, so SrO needs to be modified [20]. Modification of SrO with an alkaline halide has rarely been studied for biodiesel synthesis of waste cooking oil, especially Potassium fluoride (KF). The addition of KF can affect the activity of the catalyst. The more KF added, the greater the catalyst activity. According to the biodiesel produced, the yield will be high if the addition of KF reaches 25% and 10% [21]. The preparation of SrO-KF solid base catalyst from KF solution and SrO solids by the wet impregnation method is expected to show a much higher catalytic activity. As the best knowledge of authors, there are no studies on SrO-KF catalyst for transesterification.

Biodiesel synthesis through stirring of magnetic stirrer cause a problem of time efficiency. The conventional process takes a long time (1 to 2 hours) for the best yield of biodiesel. Alternatively, the process can be accelerated by applying ultrasonic waves [22]. Ultrasound wave will create microbubbles which reduce the size of the methanol and oil droplets to 42% smaller than that obtained by conventional methods. This increase the interfacial area between the two reactant phases, which accelerate the formation of the methyl ester (biodiesel) [23]. Ultrasonic waves can be used to increase the reaction conversion rate [24].

Based on the explanation that has been presented, this study performs transesterification of waste cooking oil under ultrasonic wave. This study explores the potency of SrO modified by KF. Various ratios and concentration of SrO-KF in this study aims to evaluate the best ratio for synthesizing SrO-KF and the best concentration for the optimum conditions for the transesterification. Therefore, the objectives of this study are: (1) to determine the optimum conditions for SrO-KF catalyst in the synthesis of biodiesel of the refined waste cooking oil and (2) to compare the results of the methyl ester with biodiesel standards.

2. Results and Discussion

Characterization of SrO-KF Catalyst

The effect of supported SrO on KF was a major objective of the present study, as these materials are highly active in transesterification without (or less) soap formation. The addition of KF with variations in the molar ratio SrO:KF of 1:1, 1:2, and 1:3. Molar comparisons are taken to see the best catalyst.

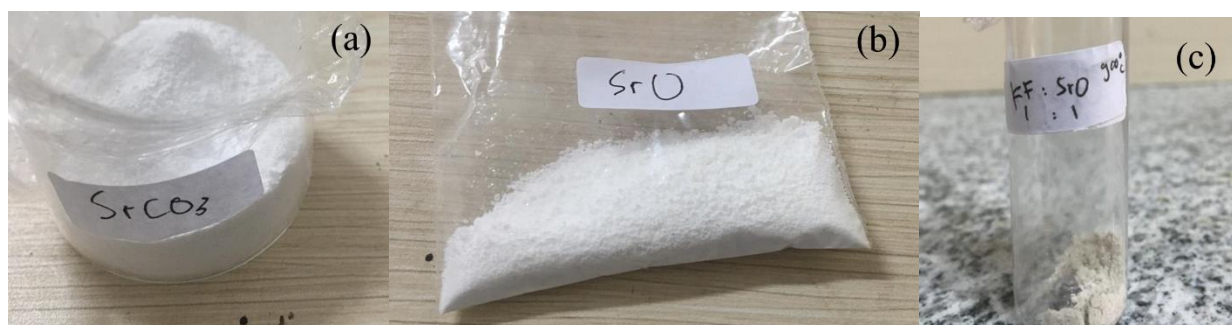


Fig. 1. (a) SrCO₃, (b) SrO obtained after calcination, and (c) SrO-KF with a ratio of 1:1.

SrO was then impregnated by KF with methanol solvent, methanol would not reduce SrO to SrCO_3 again. Furthermore, the mixture is heated in an oven to remove the solvent and calcined at 600 °C to remove any remaining water. The photograph view of the prepared catalyst can be seen in Fig 1.

XRD results of SrO-KF are shown in Fig 2.

Based on the XRD data, it was found typical peaks of SrO (31.83°, 52.35°) and KF (28.41°, 48.49°) standards. However, the peaks of 26.67°, 44.25°, 55.21°, 64.27°, 70.85°, 72.17°, 81.27°, and 87.59° form new SrF_2 crystals due to the high calcination temperature. The same thing happened to the KF/CaO catalyst, where a new crystal structure, KCaF_3 , was formed [25]. The XRD data of SrO-KF can be determined the crystal size with the Scherrer formula, so the catalyst crystal size is 12.186 nm.

XRD analysis results indexed for SrO, $\text{Sr}(\text{OH})_2$ and SrCO_3 , which enhances the formation of oxides (JCPDS 6-520). However, the pattern clearly shows the crystalline phase of some partially undecomposed SrCO_3 (JCPDS 5-418) and the formation of $\text{Sr}(\text{OH})_2$ (JCPDS 74-407) [26].

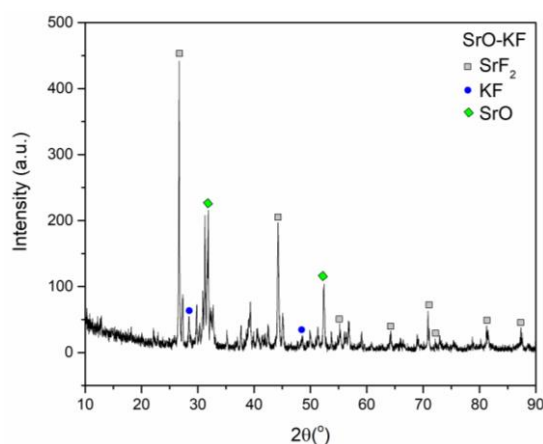


Fig. 2. XRD analysis of SrO-KF (1:1).

Fig 3 shows the SEM images of calcined SrO-KF at 800 °C. Based on the SEM image, it can be seen clearly that the SrO-KF catalyst is irregular and not homogeneous caused by calcination, resulting in a sintering process [26]. Based on the results of EDX, it proves that the catalyst contains Strontium, Oxygen, Potassium, and Fluoride elements with the appropriate atomic and weight ratios.

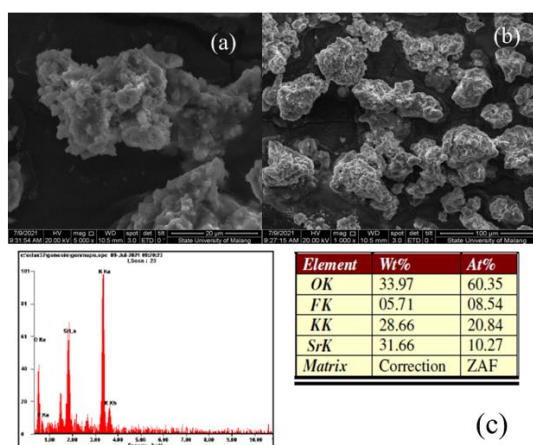


Fig. 3. SEM of SrO-KF (1:1) with size of: (a) 20 μm and (b) 100 μm, and (c) EDX analysis.

Refinement of Waste Cooking Oil using Bentonite

Waste cooking oil was refined using activated bentonite. Characterizations of oil before and after refinement have been carried out. Characteristics of oil before and after refinement are shown in Table 1.

Table 1. Characterization of Waste Cooking Oil

Parameter	Before refinement	After refinement
Density	0.9495 g/cm ³	0.9300 g/cm ³
Viscosity	44.1 cSt	31.8 cSt
Acid Number	3.3 mg KOH/g	1.8 mg KOH/g

The waste cooking oil used in this study is blackish brown in color. The refined oil using activated bentonite at 150 °C accompanied by stirring with a magnetic stirrer for 1-2 hours to reduce the water content. Bentonite is also able to bind impurities in the oil, so the color of the oil becomes brighter. The color change of waste cooking oil can be seen in Fig 4.

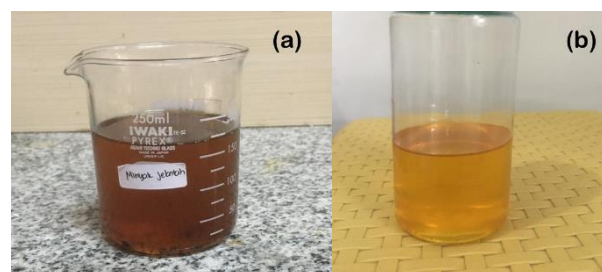


Fig. 4 Color Change in Waste Cooking Oil (a) Before Refining (b) After Refining.

Waste cooking oil has a blackish brown color before being refined, but after being refined the color changes to dark yellow. The blackish brown color of waste cooking oil is caused by the continuous use of cooking oil (repeatedly) resulting in a complex degradation reaction [27]. This reaction produces various compounds such as free fatty acids, water, peroxides, ketones and aldehydes which result in a decrease in the oil quality [28].

Transesterification of Waste Cooking Oil with SrO-KF Catalyst Assisted by Ultrasonic Wave



Fig. 5 Final Transesterification of Waste Cooking Oil with SrO-KF Catalyst in Separation Funnel.

Synthesis of biodiesel from waste cooking oil was carried out with three variations of the SrO-KF catalyst ratio, namely 1:1, 1:2, and 1:3 and variations in the concentration of catalyst addition of 2%, 3%, 4% and 5% by weight of the oil. The molar

ratio of the methanol:oil used for the transesterification reaction was 12:1 with a reaction temperature of 65 °C for 20 minutes. The success of the trans-esterification can simply be seen by the formation of two layers, the top layer of the organic layer (methyl ester) and the bottom layer of glycerol and reaction residue. The trans-esterification results are shown in Fig 5.

The results of transesterification of oil with SrO-KF catalyst at various catalyst ratios were influenced by the ratio and concentration of the catalyst used. The yields of transesterification of waste cooking oil are shown in Fig 6.

The yield of trans-esterification obtained, it can be seen that the higher the catalyst concentration, the higher yield obtained [29]. The best condition for the transesterification was the catalyst ratio SrO:KF 1:2 where at a concentration of 4% the yield produced about 84.4%. The addition of KF affects the activity of the catalyst. The more KF added, the greater the catalyst activity. However, if the addition of KF is too high, the catalyst activity will also decrease. This has been proven by previous study [25] by adding KF to CaO. Therefore, there was an increase in the yield of biodiesel at a catalyst ratio of

SrO:KF 1:1 to 1:2 with 4wt% catalyst. The previous study confirmed that using technology like microwave, ultrasonic wave, and solar radiation resulted a better yield of biodiesel than using conventional technology. Furthermore, modified SrO with KF contributed to increasing the yield of biodiesel. The comparison to the previous studies can be listed in Table 2.

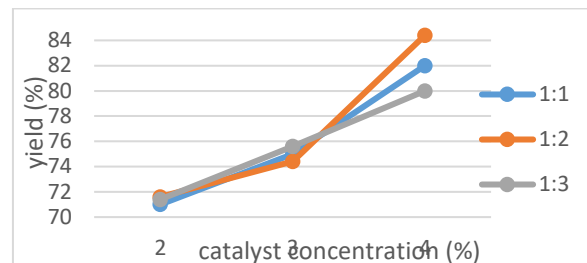


Fig. 6. Yields of Transesterification of Waste Cooking Oil in this study.

Table 2. Comparison of Transesterification of Waste Cooking Oil between Previous Study and This Study

Catalyst	Reaction condition (molar ratio, temperature, time, weight catalyst)	Yield (%)	Reference
SrO	methanol: oil (6:1), 66 °C, 4 minutes, 3% catalyst, microwave (300 W)	93	[30]
SrO	methanol: oil (6:1), 46 °C, 2 hours, 8.9 wt% catalyst, solar radiation,	98.3	[31]
SrO	methanol: oil (6:1), 80 °C, 3 minutes, 1.85% catalyst, microwave (1000 W)	93	[32]
SrO	methanol: oil (9:1), 60 °C, 2 hours, 0.1 g catalyst	48.2	[19]
KF/SiO ₂	methanol:oil (23:1), 65 °C, 1 hour, 5wt% catalyst	54.32	[33]
KF/CaO	methanol:oil (12:1), 65 °C, 2 hours, 1.6wt% catalyst	91.18	[34]
KF/CaO/La	methanol:oil (12:1), 65 °C, 1 hour, 4wt% catalyst	98.7	[35]
SrO:KF (1:2)	methanol: oil (12:1), 65 °C, 20 minutes, ultrasonic wave, 4% catalyst	85.12	This work

Characterization of The Synthesized Methyl Ester

The characterization of methyl ester was carried out on density, acid number and viscosity, the results were as shown in Table 3.

Table 3. Results of Characterization of Methyl Esters Synthesis Results Compared with SNI Biodiesel.

Characterization	Method	Result	SNI 7182:2015	ASTM
Density at 40 °C (kg/m ³)	ASTM D 1298	884	850-890	860-900
Acid Number (mg KOH/g)	ASTM D 664	0.48	0.5 max	0.8 max
Kinematic viscosity at 40 °C mm ² /s (cSt)	ASTM D 445	4.2	2.3-6.0	1.9-6.0

Based on the characterization of the methyl ester, the density, acid number and viscosity are included in the range of SNI biodiesel 7182:2015 and ASTM. Density of biodiesel will determine the level of fuel feasibility in the diesel engine [36]. High density (> the standard) cause incomplete combustion, increase engine emissions and wear. High viscosity of biodiesel affects the atomization of combustion

and other flow losses. High acid value will be corrosive to the engine because there is still free fatty acid in biodiesel [37]. Next, characterization of the synthesized methyl ester functional groups was carried out using infrared (IR). The results are shown in Fig 7.

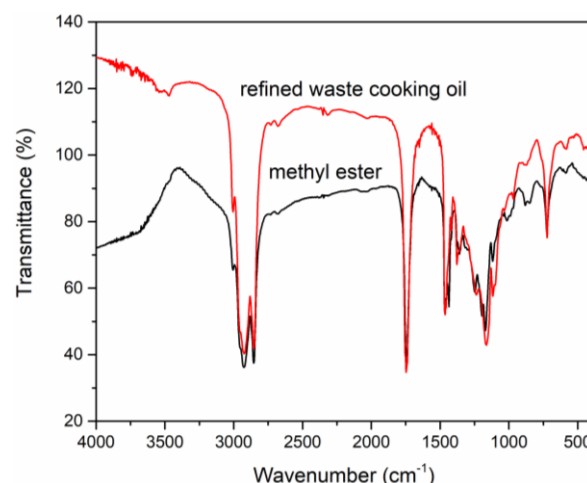


Fig. 7. FTIR of: (a) Waste Cooking Oil, and (b) the synthesized methyl ester in this study.

The results of the FT-IR spectra in **Fig 7** show the presence of the C=O functional group in ester compounds in the range of 1710–1750 cm^{-1} , the peaks of the C-O group in the range of 1050–1300 cm^{-1} , the peaks of the C-H group (sp^3) alkanes around 2800–3000 cm^{-1} , the group peak =C-H (sp^2) at 3000–3300 cm^{-1} . The results of the analysis obtained from the FTIR spectra concluded that methyl esters had been formed according to the previous study [38]. As a comparison, the FT-IR spectra of waste cooking oil in Figure (6.a), it appears that there are -OH groups in the range 3200–3600 cm^{-1} which

indicates the presence of free fatty acids [39]. Whereas in figure (6.b) the trans-esterified methyl ester mixture has no absorption around 3200 cm^{-1} which is typical for the -OH group of acids, and has been converted to an ester compound.

The components of the trans-esterified methyl ester were analyzed by Gas Chromatography and Mass Spectroscopy (GC-MS). The chromatogram results of the synthesis results are shown in Table 4.

Table 4. Synthesized Methyl Esters Using SrO-KF Catalyst Assisted by Ultrasonic Waves.

Methyl ester	Molecular Formula	% area	Retention time (minute)
Methyl caprylate	$\text{C}_8\text{H}_{16}\text{O}_2$	1.91	3.822
Methyl caprate	$\text{C}_{10}\text{H}_{20}\text{O}_2$	1.71	5.523
Methyl laurinate	$\text{C}_{12}\text{H}_{24}\text{O}_2$	10.14	7.208
Methyl miristate	$\text{C}_{14}\text{H}_{28}\text{O}_2$	6.45	8.744
Methyl palmitoleate	$\text{C}_{16}\text{H}_{30}\text{O}_2$	0.77	10.017
Methyl palmitate	$\text{C}_{17}\text{H}_{34}\text{O}_2$	25.14	10.176
Methyl isostearate	$\text{C}_{19}\text{H}_{38}\text{O}_2$	0.17	10.794
Methyl linoleate	$\text{C}_{19}\text{H}_{34}\text{O}_2$	11.27	10.910
Methyl elaidate	$\text{C}_{19}\text{H}_{36}\text{O}_2$	33.65	11.315
Methyl stearate	$\text{C}_{19}\text{H}_{38}\text{O}_2$	7.40	11.432
Methyl paulinate	$\text{C}_{20}\text{H}_{38}\text{O}_2$	0.56	12.465
Methyl isoarachidate	$\text{C}_{21}\text{H}_{42}\text{O}_2$	0.83	12.593
Total Methyl Ester		100%	

Based on the results of GC-MS, it was shown that the fatty acids of the oil include 25.14% palmitic acid, 33.65% elaidic acid, 11.27 % linoleic acid, and 7.40% stearic acid. The percentage of fatty acids as main constituent of waste cooking oil is not exactly the same as some previous study, due to the raw materials for waste cooking oil that are not the same, and the presence of unsaturated double bonds allows addition or oxidation reactions to occurs, so the results can vary. However, there are still similarities in that the largest constituents of fatty acids are palmitic acid, lauric acid, elaidic acid, and stearic acid.

3. Material and Methods

Materials

The used materials were $(\text{NH}_4)_2\text{CO}_3$ (p.a.), $\text{SrCl}_2 \cdot 6\text{H}_2\text{O}$ (p.a.), KF (p.a.), waste cooking oil, methanol, active Bentonite, aquadest, and solid MgSO_4 . The used instruments were oven, furnace, aerator, magnetic stirrer, reflux kit, thermometer, ultrasonic (Branson 1510), XRD (PanAnalyticalExpert Pro), GC-MS (Shimadzu QP2010S type), FTIR (IRPrestige 21, Shimadzu), and SEM (Inspect-S50 FEI type).

Synthesis of SrO-KF Catalyst

The first step in synthesizing strontium oxide (SrO) was calcination of SrCO_3 . The calcination was carried out to remove H_2O , CO_2 , and others on surface of the compound, so it can decrease the acidity/improve the basicity [40]. Strontium carbonate (SrCO_3) was prepared as follows: 50 mL of 5M $(\text{NH}_4)_2\text{CO}_3$ aqueous solution was mixed with 50 mL of 5M $\text{SrCl}_2 \cdot 6\text{H}_2\text{O}$ solution and stirred with a magnetic stirrer for 60 minutes at 80 °C. The white strontium carbonate powder was then washed 3 times with aquadest and dried at 100 °C for 24 hours. Solid SrO can be obtained by calcining SrCO_3 at 1100 °C for 180 minutes at a heating rate of 10 °C/min [26].

SrO-KF nanoparticle catalysts were prepared by the impregnation method. Potassium fluoride (KF) was added to SrO. Variations in the KF and SrO mole ratios were 1:1, 1:2, and

1:3. Then, the two substances were mixed while crushed until well blended. Then, distilled water was added until it became a paste. After that, it was heated for 5 hours at 105 °C and followed by calcination at 800 °C for 4 hours [25].

Furthermore, the synthesized SrO-KF catalysts were characterized by X-Ray Diffraction (XRD) and Scanning Electron Microscopy with energy dispersive X-ray spectroscopy (SEM-EDX). XRD used instrument of PANalytical X'Pert PRO in order to get the phase crystal of the material. SEM-EDX used instrument of FEI Inspect-S50 in order to see the morphology and elemental mapping of the material.

Refinement of Waste Cooking Oil

Firstly, waste cooking oil was filtered assisted by a Buchner filter. Waste cooking oil was washed with warm aquadest with a volume ratio of oil: water (1:3). Activated Bentonite was added to the oil at a rate of 20% by weight of the oil. The mixture was heated to a temperature of 150 °C with stirring at a speed of 250–300 rpm. The mixture was cooled and separated through a Buchner filter. This process took time of 4 hours for 500 mL of waste cooking oil.

Transesterification of Waste Cooking Oil Catalyzed by SrO-KF

The transesterification was carried out using a 100 mL Erlenmeyer. 25 g of waste cooking oil was put and added with methanol with a molar ratio of methanol:oil about 12:1. Furthermore, SrO-KF catalyst was added at 2%, 3%, and 4% by weight of oil as a variation of study. The reaction was carried out using ultrasonic waves at 65 °C for 20 minutes. After that, it was put into a separating funnel until two layers were formed and separated. Then, the oil was washed with hot aquadest and added solid MgSO_4 and then filtered. The biodiesel yields were analyzed by GC-MS and FT-IR [26]. Furthermore, characterization was carried out on waste cooking oil and also on trans-esterified biodiesel which included parameters of viscosity, density, acid number, and

free fatty acid content.

4. Conclusions

The use of SrO-KF catalyst for the transesterification was analyzed by various instruments, namely XRD, SEM-EDX. Through the analysis of the catalyst, it was indicated the presence of SrF₂, SrO and KF in the catalyst. The higher the catalyst concentration, the more biodiesel yield. The best conditions for the transesterification were using SrO-KF catalyst with a ratio of 1:2 and a concentration of 4% w/w to oil which produced a yield of 85.12% with a molar ratio of methanol:oil of 12:1 and a reaction temperature of 65 °C for 20 minutes. In the results of the GC-MS analysis, the highest percentage of fatty acids in the synthesized methyl ester was 25.14% methyl palmitate and 33.65% methyl elaidate. The characteristic of the methyl ester synthesized from waste cooking oil using SrO-KF catalyst resulted in viscosity of 4.2 cSt, density of 884 kg/m³, and acid number of 0.48 mg KOH/g. Based on the characterization, the methyl ester synthesized from waste cooking oil with SrO-KF catalyst using ultrasonic waves is in accordance with SNI and ASTM. This study showed that KF-modified SrO contribute to the increasing of catalytic activity in the transesterification of waste cooking oil.

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Author Contributions

Aman Santoso: Conceptualization, Supervision, Methodology, writing – Review & Editing and Funding Acquisition. Laili Ramadhan: Investigation, Data Curation and Writing – Original Draft. Bambang Susilo: Validation and Writing – Review & Editing. Sukarni Sukarni: Writing – Review & Editing. Anugrah Ricky Wijaya: Validation and Draft and Writing – Review & Editing. Sumari Sumari: Validation, Supervision, and Writing – Review & Editing. Muntholib Muntholib: Writing – Original Draft and Writing – Review & Editing. Indah Nur Pramesti: Formal Analysis and Writing – Review & Editing. Muhammad Roy Asrori: Visualization, writing – Original Draft, Writing – Review & Editing.

References and Notes

- [1] OECD/FAO, "OECD-FAO Agricultural Outlook," 2021.
- [2] Sumari, S.; Santoso, A.; Asrori, M. R. *Orbital: Electron. J. Chem.* **2021**, *13*, 385. [\[Crossref\]](#)
- [3] Kamaronzaman, M. F. F.; Kahar, H.; Hassan, N.; Hanafi, M. F.; Sapawe, N. *Mater. Today Proc.* **2020**, *31*, 329. [\[Crossref\]](#)
- [4] Foo, W. H. *et al. Fuel* **2022**, *324*, 124539. [\[Crossref\]](#)
- [5] Foo, W. H.; Chia, W. Y.; Tang, D. Y. Y.; Koay, S. S. N.; Lim, S. S.; Chew, K. W. *J. Hazard. Mater.* **2021**, *417*, 126129. [\[Crossref\]](#)
- [6] Mahdi, H. I.; Bazargan, McKay, G.; Azelee, N. I. W.; Meili, L. *Chem. Eng. Res. Des.* **2021**, *174*, 158. [\[Crossref\]](#)
- [7] Primadi, T. R.; Fajaroh, F.; Santoso, A.; Nazriati.; Ciptawati, E. *Key Eng. Mater.* **2020**, *851*, 184. [\[Crossref\]](#)
- [8] Mannu, A.; Vlahopoulou, G.; Sireus, V.; Petretto, G. L.; Mulas, G.; Garroni, S. *Nat. Prod. Commun.* **2018**, *13*, 613. [\[Crossref\]](#)
- [9] Farouk, H.; Zahraee, S. M.; Atabani, A. E.; Jaafar, M. N. M.; Alhassan, F. H. *Biofuels* **2020**, *11*, 655. [\[Crossref\]](#)
- [10] Mahdi, H. I. *et al. Chemosphere* **2023**, *319*, 138003. [\[Crossref\]](#)
- [11] Santoso, A. *et al. Key Eng. Mater.* **2020**, *851*, 164. [\[Crossref\]](#)
- [12] Santoso, A.; Putri, D. E. K.; Rusdi, M.; Sumari, S.; Wijaya, A. R.; Rachman, I. B. *AIP Conf. Proc.* **2021**, *2330*, 070008. [\[Crossref\]](#)
- [13] Mohamed, E. A.; Betiha, M. A.; Negm, N. A. *Energy & Fuels* **2023**, *37*, 2631. [\[Crossref\]](#)
- [14] Ahmed, M. *et al. Energy Convers. Manag.* **2023**, *280*, 116821. [\[Crossref\]](#)
- [15] Oloyede, C. T.; Jekayinfa, S. O.; Alade, A. O.; Ogunkunle, O.; Otung, N.-A. U.; Laseinde, O. T. *Eng. Reports* **2023**, *5*, e12585. [\[Crossref\]](#)
- [16] Aderibigbe, F. A. *et al. ChemBioEng Rev.* **2023**, *10*, 293. [\[Crossref\]](#)
- [17] Orege, J. I. *et al. Energy Convers. Manag.* **2022**, *258*, 115406. [\[Crossref\]](#)
- [18] Prokaew, A.; Smith, S. M.; Luengnaruemitchai, A.; Kandiah, M.; Boonyeon, S. *J. Met. Mater. Miner.* **2022**, *32*, 79. [\[Crossref\]](#)
- [19] Shahbazi, F.; Mahdavi, V.; Zolgharnein, J. *J. Iran. Chem. Soc.* **2020**, *17*, 333. [\[Crossref\]](#)
- [20] De Abreu, W. C.; De Moura, C. V. R.; Costa, J. C. S.; De Moura, E. M. *J. Braz. Chem. Soc.* **2017**, *28*, 319. [\[Crossref\]](#)
- [21] Hu, S.; Guan, Y.; Wang, Y.; Han, H. *Appl. Energy* **2011**, *88*, 2685. [\[Crossref\]](#)
- [22] Santoso, A.; Wijaya, A. R.; Rahmadani, A.; Sukarianingsih, D.; Putri, D. E. K.; Sumari, S. *AIP Conf. Proc.* **2021**, *2330*, 70009. [\[Crossref\]](#)
- [23] Chipurici, P. *et al. Ultrason. Sonochem.* **2019**, *57*, 38. [\[Crossref\]](#)
- [24] Bashir, M. A.; Wu, S.; Zhu, J.; Krosuri, A.; Khan, M. U.; Ndeddy Aka, R. J. *Fuel Process. Technol.* **2022**, *227*, 107120. [\[Crossref\]](#)
- [25] Wen, L.; Wang, Y.; Lu, D.; Hu, S.; Han, H. *Fuel* **2010**, *89*, 2267. [\[Crossref\]](#)
- [26] Falcão, M. S.; Garcia, M. A. S.; de Moura, C. V. R.; Nicolodi, S.; de Moura, E. M. *J. Braz. Chem. Soc.* **2018**, *29*, 845. [\[Crossref\]](#)
- [27] Santoso, A. *et al. AIMS Energy* **2022**, *10*, 1059. [\[Crossref\]](#)
- [28] Mannu, A. *et al. Resources* **2019**, *8*, 108. [\[Crossref\]](#)
- [29] Zhang, M. *et al. Environ. Res.* **2022**, *205*, 112509. [\[Crossref\]](#)
- [30] Lee, H. *et al. Chem. Eng. Technol.* **2018**, *41*, 192. [\[Crossref\]](#)
- [31] Tabah, B.; Nagvenkar, A. P.; Perkas, N.; Gedanken, A. *Energy & Fuels* **2017**, *31*, 6228. [\[Crossref\]](#)
- [32] Priambodo, R.; Chen, T.-C.; Lu, M.-C.; Gedanken, A.; Liao, J.-D.; Huang, Y.-H. *Energy Procedia* **2015**, *75*, 84. [\[Crossref\]](#)
- [33] Aneu, A.; Wijaya, K.; Syoufian, A. *J. Porous Mater.* **2022**, *29*, 1321. [\[Crossref\]](#)
- [34] Anbia, M.; Masoomi, S.; Sedaghat, S.; Sepehrian, M. *J.*

- Environ. Treat. Tech.* **2019**, 7, 103.
- [35] Yang, L. *et al. Int. J. Green Energy* **2017**, 14, 784. [\[Crossref\]](#)
- [36] Tomić, M.; Đurišić-Mladenović, N.; Mičić, R.; Simikić, M.; Savin, L. *Fuel* **2019**, 235, 269. [\[Crossref\]](#)
- [37] Rahadiani, E. S.; Yerizam, Y.; Martha, M. *Indones. J. Fundam. Appl. Chem.* **2018**, 3, 77. [\[Crossref\]](#)
- [38] Setiadji, S. *et al. J. Kim. Val.* **2017**, 3, 1. [\[Crossref\]](#)
- [39] Abdullah, Sianipar, R. N. R.; Ariyani, D.; Nata, I. F. *Sustain. Environ. Res.* **2017**, 27, 291. [\[Crossref\]](#)
- [40] Rashid, U.; Soltani, S.; Al-Resayes, S. I.; Nehdi, I. A.: 11-metal oxide catalysts for biodiesel production. In: Wu, Y.B.T.-M.O. in ET (eds.). *Met. Oxides*. Elsevier (2018), pp. 303–319. [\[Crossref\]](#)

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