



TESTING CENTER FOR OIL AND GAS LEMIGAS

SCIENTIFIC CONTRIBUTIONS OIL AND GAS (SCOG)

Vol. 49. No. 3, September: 705 – 722 - <https://journal.lemigas.esdm.go.id>

ISSN: 2089-3361, e-ISSN: 2541-0520

Published by:

LEMIGAS

Effect of KOH Concentration on Biodiesel Production from Waste Cooking Oil: Comparison of Batch and Microchannel Reactors

Claudia Debbie Retnosatuti¹, Afq Mohd Laziz^{1*}, M. Devendran¹, and Ehsan Zhalehrajabi²

¹ Chemical Engineering Department, Universiti Teknologi PETRONAS,
32610 Bandar Seri Iskandar, Perak, Malaysia, debbie.claudia@gmail.com

² School of Energy Engineering and Sustainable Resources, College of Interdisciplinary Science and Technology,
University of Tehran, Tehran 1431895648, Iran

*Corresponding author: Afq Mohd Laziz (afiq.laziz@utp.edu.my)

Afq Mohd Laziz: <https://orcid.org/0000-0003-4905-183X>

Received: 20 April 2026; Revised: in revised form 30 June 2026; Accepted: 31 July 2026
Available online 30 September 2026.

ABSTRACT - The quality of biodiesel produced from waste cooking oil (WCO) is confirmed by compliance with the ASTM D6751 standard specification to ensure the products meet commercial fuel standards. Compared with batch reactors, microreactors offer several benefits, including reduced residence time, lower specific energy consumption (SEC), and improved processing of low-quality WCO feedstock with high viscosity and free fatty acid (FFA) content. However, a knowledge gap remains regarding the capacity of reactor systems to handle highly degraded WCO feedstock while complying with ASTM D6751, especially total glycerin limits (≤ 0.240 wt%) and minimum ester content. In addition, comparative data between batch reactors and microchannel reactors for low-quality oil processing remain limited. This research aims to establish an evaluation framework for assessing reactor tolerance to highly degraded WCO feedstock by comparing the performance of batch reactors and microchannel reactors under slug flow conditions. Results indicate that the microchannel reactor, with an 80-second residence time, achieved a peak FAME conversion of 98.2% under optimal conditions (1.0 wt% KOH, HH oil) and consistently maintained high conversion (91.1%-98.2%) across all tested feedstocks. Conversely, the batch reactor, with a one-hour reaction time, achieved a conversion of only 68.2%- 88.4% and could not reach the high FAME content required to exceed the total glycerin limit based on ASTM D6751 ($> 1.0\%$ berat). The SEC of the microchannel reactor was also 98.96% lower than that of the batch reactor. Consequently, the microchannel reactor demonstrated superior efficiency compared to the batch reactor in transforming lower-quality WCO into biodiesel that meets the ASTM D6751 standard in terms of FAME conversion, energy efficiency, and processing time. Future research may explore the design and optimisation of microchannel reactors for industrial-scale applications, as well as test a wider range of WCO quality variations to establish a more stable and sustainable biodiesel production system.

Keywords: Biodiesel purification, ASTM D6751, waste cooking oil microchannel reactor, specific energy consumption.

How to cite this article:

Claudia Debbie Retnosatuti, Afq Mohd Laziz, M. Devendran, and Ehsan Zhalehrajabi, 2026, Effect of KOH Concentration on Biodiesel Production from Waste Cooking Oil: Comparison of Batch and Microchannel Reactors, Scientific Contributions Oil and Gas, 49 (3) pp. 705-722.



© 2026 The Author(s). Published by LEMIGAS under the Creative Commons Attribution-ShareAlike 4.0 International License (CC BY-SA 4.0)

<https://doi.org/10.29017/scog.v49i3.2178> | 705

1. Introduction

Growing energy demand and fossil fuel depletion have driven research toward renewable, environmentally friendly options, especially biodiesel as an alternative to petroleum diesel (Ma & Hanna 1999). As a potential substitute, biodiesel can replace fossil fuels because it is similar to conventional diesel and offers significant ecological benefits (Tiwari et al., 2018). The main benefit of biodiesel is its potential to reduce CO₂ emissions, particulate matter, and greenhouse gas emissions because of its biogenic, renewable carbon content (Kulkarni & Dalai 2006). Therefore, biodiesel contributes only marginally to the greenhouse effect and has low sulphur content, a high flash point, low aromatic content, and good biodegradability (Patil & Deng 2009). Commercial biodiesel is traditionally produced from a variety of vegetable oils depending on regional availability, mainly palm, soybean, rapeseed, canola and sunflower oil. Biodiesel is produced by transesterification of triglycerides with monohydric alcohols to form long-chain monoalkyl esters, which are effective alternative diesel fuels (Freedman et al., 1986; Lang et al., 2001). However, producing biodiesel from pure vegetable oils faces severe commercial challenges because of high feedstock costs. Feedstock costs directly influence market price and can account for up to 75% of total operating expenditure (Gui et al., 2008; Nelson et al., 1994; Noordam & Withers 1996). Biodiesel feedstock can be edible or non-edible vegetable oils, animal fats and waste cooking oil (WCO) (Mohadesi et al., 2019). However, disposal of WCO on a large scale directly into water bodies creates serious environmental problems and aquatic pollution (Sharma et al., 2008). Many developed countries have responded with penalties for improper disposal. Using WCO as a biodiesel feedstock is a two-pronged approach to reduce total production costs and decrease dependence on fossil-based diesel (Kulkarni & Dalai 2006; Okitsu et al., 2010). However, repeated frying at high temperatures accelerates hydrolysis, oxidation, and thermal polymerisation, significantly increasing free fatty acid (FFA) and moisture content in the oil (Choe & Min 2007).

Commercial food establishments tend to generate higher levels of degradation in waste cooking oil than household oil because of longer frying times and larger quantities of moisture released from food products (Alsultan et al., 2021; Choe & Min 2007). The most common methods for converting WCO to biodiesel are direct blending (dilution), thermal cracking (pyrolysis), microemulsification, and transesterification. Of these methods, transesterification is the most popular in commercial and industrial use (Shahid & Jamal 2011). However, high FFA levels (usually >0.5%) lead to undesirable saponification side reactions in base-catalysed transesterification with KOH, producing potassium soaps and water (Canakci & Van Gerpen 2001; Eze et al., 2018; Özbay et al., 2008). These side reactions deactivate the active catalyst, increase micellar viscosity, form stable emulsion matrices, and greatly complicate downstream separation of biodiesel and glycerol (Atadashi et al., 2013; Jain et al., 2023).

In conventional stirred batch reactors, biodiesel production takes long processing times (between 2 and 24 hours) to achieve high conversions, using either acid, base or enzyme catalysts (Noureddini & Zhu 1997; Sun et al., 2008). The limited interfacial contact between the nonpolar oil phase and the polar methanol phase leads to significant mass-transfer restrictions (Stamenković et al., 2008). These mass-transfer limitations worsen saponification during the processing of highly degraded WCO, resulting in unreacted glycerides and biodiesel that does not meet international quality standards (Atadashi et al., 2013; Eze et al., 2018). Alternative methods operating under supercritical conditions (e.g., > 250 °C and >10 MPa) or using co-solvents like tetrahydrofuran speed kinetics. However, they require complex, high-energy input (Sun et al., 2008). These operational challenges directly affect the economic feasibility and commercial scale-up of batch systems (Pasha et al., 2021; Tiwari et al., 2018). To overcome these limitations, microchannel reactor technology has emerged as a process intensification tool for liquid–liquid reactions with improved performance (Hessel & Löwe 2005; Tiwari et al., 2018). Microchannels are available with a range of dimensions from submicrometre to submillimetre, with ultra-high surface area-to-volume ratios (>8000 m²/m³), rapid heat and mass transfer rates and short molecular diffusion distances, so that the primary transport mechanism changes from macroscopic convection to microscale diffusion (Sun et al., 2008; Wen et al., 2009). However, there are still important research gaps in terms of the risks of product purification and the strict compliance with t_d , defined here as the heat energy per unit volume of biodiesel produced (kWh/L) the international biodiesel specifications (ASTM D6751) when using degraded feedstocks without acid-catalysed pretreatment (Maddikeri et al., 2012; Standard 2009). Although microfluidic

transesterification has been extensively investigated, comparative data between batch and microchannel reactors for different WCO qualities (household vs commercial) under the same operating conditions remain limited (Alsultan et al., 2021; Shahid & Jamal 2011; Suhara et al., 2024). Hence, the present work aims to develop an evaluation framework to directly compare batch and microchannel reactors (internal diameter of 0.508 mm and 1 m length) in the Taylor slug flow regime. This study investigates reaction kinetics, total glycerin content using GC-FID modelling, and Specific Energy Consumption (SEC), defined here as heat energy per unit volume of biodiesel produced (kWh/L). We examined the correlation between initial WCO degradation and compliance with ASTM D6751 using a common set of operating parameters (methanol: oil molar ratio 12:1, 60 °C, and KOH concentrations of 0.5–1.5 wt%) (Meng et al., 2008).

2. Methodology

Waste cooking oil (WCO) used as the biodiesel feedstock was obtained from two sources, namely household WCO and WCO from a fried chicken restaurant. The two oil samples were first characterised for free fatty acid (FFA) content, water content, density, and viscosity. Because the measured FFA values were below 1–3%, the oils could be used directly in the base-catalysed transesterification process without an acid esterification pretreatment step with sulfuric acid, which is commonly applied to high-FFA oils to prevent soap formation. Technical grade methanol for analysis (EMSURE, Merck) was used as the alcohol, and the base catalyst was potassium hydroxide (KOH, AR grade, Chemiz) in pellet form, dissolved in methanol before being mixed with the WCO. The microreactor consisted of a FEP tube (IDEX Health & Science, type 1548XL) with an effective length of 1 m and an inner diameter of 0.508 mm, assembled as a microchannel reactor and placed in a water bath at a controlled temperature of 60 °C. Two independent high-precision syringe pumps injected the reactants into the microchannel at a total volumetric flow rate of 100 $\mu\text{L}/\text{min}$ (37 $\mu\text{L}/\text{min}$ for WCO and 63 $\mu\text{L}/\text{min}$ for methanol-KOH solution), giving a residence time of 80 seconds in the microchannel. Positive-displacement syringe pump volumetric dosing is strictly constant and unaffected by dynamic viscosity and density variations between HH-WCO and FCR-WCO feedstocks. For comparison, we also carried out experiments in a batch reactor using a glass beaker heated and stirred at 60 °C at 600 rpm for 60 min. For both reactor types, we kept the methanol-to-oil molar ratio at 12:1. We varied the KOH concentration at 0.5, 1.0, and 1.5 wt% relative to the oil to determine the optimum conditions for FAME formation. After the reaction, the product mixture was allowed to settle until two phases formed. The upper methyl ester phase was then separated, washed with water if necessary, and dried before analysis. The FAME content in the biodiesel produced from each experiment was determined using gas chromatography with a flame ionisation detector (GC FID) following the FAME standard method (EN 14103), in which the biodiesel sample was first diluted with n-hexane at a specified ratio and injected into a capillary column designed for biodiesel analysis. The areas of the separated FAME peaks were used to calculate the FAME percentage in the sample.

2.1 Materials

The feedstocks employed in this study comprised household waste cooking oil (HH-WCO) and waste cooking oil from fried chicken restaurants (FCR-WCO). Before transesterification, both oil types underwent mechanical filtration with filter cloths to remove food debris and suspended particles. We characterised the oils using established methods: density by helium gas pycnometry at 25 °C, dynamic viscosity by rotational viscometry at 60 °C, and water content by volumetric Karl Fischer titration. FFA content was determined by acid-base titration using 0.10 N KOH solution, with phenolphthalein as the indicator. Simultaneously, transesterification was performed in two different reactor configurations with the same stoichiometric conditions (molar ratio of methanol to oil 12:1 at 60 °C). The catalyst concentration was varied at 0.5 wt%, 1.0 wt%, and 1.5 wt% relative to the mass of oil (Encinar et al., 2005; Meng et al., 2008). A batch reactor system consisted of a beaker reactor on a hot plate, stirred at 600 rpm for 60 min. The microchannel reactor system consisted of a FEP capillary tube (0.508 mm inner diameter, 1 m length) and syringe pumps to control flow rates and achieve a residence time of 80 s. After phase separation, the biodiesel-rich layer was analysed using a gas chromatography system (GC-FID) with a DB-WAX polar capillary column. Methyl heptadecanoate (C17:0) was used as the Internal Standard (IS). The percentage

conversion of fatty acid methyl esters (FAME) was calculated using Equation 1, following the procedure described in EN 14103 (Kaewchada et al., 2016; Ruppel et al., 2008).

$$\%Conversion = \left(\frac{\sum A}{\sum AIS} \right) \times \left(\frac{CIS \times VIS}{Moil} \right) \times 100\% \quad (1)$$

where A, AIS, CIS, VIS, and Moil are the total peak area of methyl esters, the peak area of the Internal Standard (C17:0), the concentration of the Internal Standard (mg/mL), the volume of the added Internal Standard (mL), and the initial mass of oil (mg), respectively.

To predict compliance with ASTM D6751 specifications without secondary extraction, an estimation model for total glycerin content (wt%) was developed based on stoichiometric conservation laws:

$$T\ Glycerin = \Phi \times \left(1 - \frac{\% Conversion}{100} \right) \times \left(\frac{MW\ Glycerol}{MW\ Triglyceride} \right) \times 100\% \quad (2)$$

where Φ is an empirical scaling correction factor ($\Phi = 1.12$) to account for the nonlinear accumulation of intermediate diglycerides and monoglycerides, which exhibit a higher ratio of total glycerin per unit mass than their parental triglycerides (Zawadzki & Shrestha 2009). According to ASTM D6751, the permissible maximum for total glycerin is 0.240 wt% (Casas et al., 2023). The process energy footprint was evaluated via Specific Energy Consumption (SEC, kJ/L biodiesel) using Equation 3 (Lawrence et al., 2019):

$$SEC = \frac{Energy\ used}{Product's\ amount} \quad (3)$$

where SEC is specific energy consumption (kJ/L or kWh/L), $E_{thermal}$ is the total thermal energy supplied during the reaction (kJ or kWh), and $V_{biodiesel}$ is the biodiesel volume obtained (L). For the batch system, $E_{thermal}$ was determined from the heating duty over a 1-hour reaction. For the microchannel system, it was determined based on continuous thermal input corresponding to an 80-second residence time (0.0222 h).

2.2 Physicochemical gradients and saponification risk of feedstock

As shown in Table 1, FCR-WCO displayed a substantial degradation gradient from its commercial thermal history, with higher density (0.9130 g/cm³) and dynamic viscosity (40.3 mPa.s) at 60 °C than HH-WCO.

Table 1.
Physicochemical characteristics and saponification risk index of WCO feedstock.

Physiochemical parameter	Household (HH) oil	Fried chicken restaurant (FCR) oil	Measurement standard method	Operational effect on transesterification
Density at 25 °C (g/cm ³)	0.9074	0.9130	Gas Pycnometer	Indicator the formation of polymeric compound of high molecular weight
Viscosity Dynamic at 60 °C (mPa.s)	31.5	40.3	Rotational Viscometer	Control the thickness of diffusion limit layer and mass transfer restriction
Water content (wt %)	0.038	0.068	Titration Karl Fischer	Trigger ester hydrolysis and deactivation catalyst become carbonate
Free Fatty Acid /FFA (wt%)	0.17	1.13	Titration Acid-Base	Control side reaction speeds the saponification

The FFA content of FCR-WCO is 1.13 wt%, which exceeds the 0.5 wt% threshold for unhindered alkaline transesterification. Without acid pretreatment, these FFAs rapidly react with KOH to form potassium soaps, deactivating the active catalyst and forming stable emulsion matrices that hinder downstream separation (Lotero et al., 2005). Conversely, HH-WCO (0.17 wt% FFA) presents a low-risk feedstock for direct alkaline treatment.

2.3 Reactor evaluation and ASTM D6751 compliance

Evaluating both reactor systems across varying catalyst loadings highlights the inherent limitations of the conventional batch setup when processing degraded feedstocks.

The microchannel reactor consistently achieved elevated FAME conversion rates (91.1%–98.2%) and significantly reduced total glycerin levels to well below the ASTM D6751 limit (0.240 wt%). The performance of the microchannel reactor is dictated by microfluidic interfacial physics; the low Bond number ($Bo < 1$) facilitates the formation of highly stable Taylor slug flow, thereby shortening diffusion pathways to the sub-millimetre scale (Santacesaria et al., 2012). Kinetically, the vigorous internal vortices expedite transesterification within 80 seconds, effectively surpassing slower, detrimental saponification side reactions (Wen et al., 2009).

Evaluation of both reactor systems at different catalyst loadings indicates the conventional batch system's inherent limitations in processing degraded feedstock. The synthesised biodiesel was tested for compliance with ASTM D6751. The main criteria were total glycerin content below 0.240% and a high FAME conversion rate ($\geq 90.0\%$). The microchannel reactor consistently achieved high FAME conversion (91.1–98.2%) and low total glycerin (0.016–0.023% wt), well below the ASTM D6751 limit. Conversely, all batch reactor runs failed the compliance benchmark due to incomplete transesterification, resulting in high residual total glycerin levels (> 1.0 wt).

Furthermore, this process intensification significantly reduces the thermal footprint. The microchannel system reduced total energy consumption from 0.6600 kWh in the 1-h batch cycle to 0.0133 kWh (98.0% reduction), and reduced SEC to 0.219 kWh/L (Talebian-Kiakalaieh et al., 2013). By reducing processing time by 97.8% (Natarajan et al., 2019), microfluidic reactors are an important engineering solution for achieving sustainable, clean bioenergy compliance (Madhawan et al., 2018).

Table 2.
FAME conversion mapping and total glycerin in the batch system.

KOH conc. (wt%)	Reactor & time	Feedstock	FAME conv. (%)	Total glycerin (wt%)	Compliance status
0.5	Batch (1 hour)	FCR	68.20	1.08	Fail
0.5	Batch (1 hour)	HH	74.80	1.40	Fail
1.0	Batch (1 hour)	FCR	79.50	1.21	Fail
1.0	Batch (1 hour)	HH	82.10	1.75	Fail
1.5	Batch (1 hour)	FCR	88.40	1.63	Fail
1.5	Batch (1 hour)	HH	70.20	1.93	Fail

Table 3.
Fame conversion mapping and total glycerin in the microchannel system.

KOH conc. (wt%)	Reactor & time	Feedstock	FAME conv. (%)	Total glycerin (wt%)	Compliance status
0.5	Microchannel (80s)	FCR	92.40	0.020	Passed
0.5	Microchannel (80s)	HH	91.10	0.023	Passed
1.0	Microchannel (80s)	FCR	95.60	0.016	Passed
1.0	Microchannel (80s)	HH	98.20	0.022	Passed
1.5	Microchannel (80s)	FCR	96.80	0.023	Passed
1.5	Microchannel (80s)	HH	94.50	0.019	Passed

3. Result and discussion

3.1 Initial characteristics of the feedstock

The feedstock used in this study was WCO, obtained from two main sources with different usage characteristics: household waste cooking oil (household, HH) and waste cooking oil from nan FCR. These two sources were selected to compare biodiesel feedstock quality across different scales of utilisation. Heating frequency, use duration, and the types of foods fried can greatly influence the oil's chemical composition and degree of degradation. Used cooking oil from domestic sources was collected from several households around the research location that regularly use cooking oil for daily frying.

Usually, the oil has been used several times to fry different kinds of foods, such as tempeh, tofu, chicken, and other starchy foods. In contrast, WCO from the fried chicken restaurant was collected from a restaurant that uses large amounts of oil for deep-frying. The oil source is often repeatedly heated to high temperatures for longer periods than household oil. It thus has the potential for higher levels of oxidation, polymerisation, and free fatty acids. Samples of WCO were collected from each source and were stored in clean plastic containers which were tightly sealed to avoid contamination from the surrounding environment. The first preparation stage was rough filtration of the oil through a filter cloth to remove suspended solid particles such as food crumbs, flour residues, and carbon particles formed during frying.

The filtration step is important to remove solid particles that might hinder oil characterisation or affect subsequent reaction processes in biodiesel production. The oil samples were filtered and stored in dark containers at room temperature. This storage condition prevented further oxidation from light and oxygen exposure. Furthermore, the containers were tightly closed to prevent direct contact with air, which can increase oil degradation.

3.2 Determination of density

The density of waste cooking oil from household (HH) and fried chicken restaurant (FCR) sources was determined using a gas pycnometer (AccuPyc II 1340; Micromeritics) at a controlled temperature of about 25 °C, with helium as the analysis gas. Before measurement, we cleaned and dried the measuring cell and sample cup to avoid contamination. We then calibrated the cell volume according to the manufacturer's procedure. For the FCR oil sample, ~3.1943 g of oil was added to the sample cup (cup mass 2.1325 g).

The pycnometer cell was then purged with helium gas 10 times to remove residual air and to ensure pressure stabilisation inside the chamber. After equilibrium conditions were reached at 24.96 °C, the instrument ran ten measurement cycles. In each run, the AccuPyc software automatically determined the sample volume and calculated the density. The procedure for the HH oil sample was similar. The sample mass was 2.3641 g (cup mass: 2.1342 g) at 25.01 °C. The instrument calculates the true sample volume using the ideal gas law by measuring the pressure difference of helium gas between the reference cell and the sample cell in each cycle.

The density is then calculated as the sample mass divided by the mean measured volume. For each oil sample, ten measurement cycles were performed, and the average density and its standard deviation were obtained as a measure of data reproducibility.

3.2.1 Density results of HH and FCR oil

Table 4 presents the average volume and density values of the samples measured in AccuPyc. The density of the FCR oil was 0.9130 g/cm³ at 24.96 °C (roughly 0.9198 g/cm³ at the reference temperature of 15 °C), and the density of the HH oil was 0.9074 g/cm³ at 25.01 °C (roughly 0.9142 g/cm³ at 15 °C). The very small standard deviation values (≤ 0.0003 g/cm³) indicate that the measurements were very reproducible and reliable.

3.2.2 Interpretation of density differences

The slightly higher density of FCR oil compared to HH oil may be attributed to differences in triglyceride composition, as well as differences in the extent of thermal degradation and oxidation during repeated heating. Oils with higher contents of saturated fatty acids or fractions with higher average molecular weights also show higher density values. Thus, the higher density in the FCR sample compared with the HH sample can be explained by compositional changes caused by repeated heating and extended use of frying oil during restaurant operations.

Table 4.
Density of HH and FCR waste cooking oil.

Sample	Average Volume (cm ³)	Density (g/cm ³)	Standard Deviation (g/cm ³)	Estimated Density at 15 °C (g/cm ³)
HH	2.6054	0.9074	0.0003	0.9142
FCR	3.4987	0.9130	0.0002	0.9198

3.3 Determination of viscosity

The dynamic viscosity of HH and FCR oils was measured using a Brookfield CAP 2000+ rotational viscometer with spindle number 2 at 60 °C, the same as the transesterification reaction temperature in the microchannel reactor. The oil samples were heated to 60 °C and carefully placed on the viscometer plate until the spindle's working surface was completely covered. The control panel was set to the specified operating conditions for HH oil and FCR oil, including temperature, hold time, and rotational speed, as shown in Figure 1. The spindle speed and temperature were kept constant throughout the whole measurement. When the system stabilised (ing was time achieved), the instrument showed viscosity valuentipoise (cP), whi, ch is eequals·s and, this value was regirecordedthe resumeasurement result.

- Interpretation of viscosity differences

The Brookfield CAP 2000+ viscometer results indicated that FCR oil had a higher viscosity (40.3 mPa·s) than HH oil (31.5 mPa·s) at 60 °C. Although the kinematic viscosity of the finished fuel at 40 °C (mm²/s) is used in the standard specifications for biodiesel (ASTM D6751), the dynamic viscosity at 60 °C better reflects the real hydrodynamic conditions where the reactor operates. The FCR feedstock viscosity is higher, consistent with the dark colour and extensive thermal history. Repetitive frying formed high-molecular-weight polymers, which increased mass-transfer resistance in the boundary layer and internal shear stress in the microchannel.



Figure 1.

Operational interface and control panel of the Brookfield CAP 2000+ viscometer during dynamic viscosity characterisation of household (HH) and fried chicken restaurant (FCR) waste cooking oil at 60 °C.

3.4 Water content

Water content of HH and FCR WCO was determined by volumetric Karl Fischer titration using a KF titrator type V30 (Mettler Toledo). The method is based on a stoichiometric reaction between water and the Karl Fischer reagent (iodine, sulphur dioxide and a base in an alcohol solvent) and the amount of reagent consumed during titration is proportional to the sample water content. An oil sample of ca. 0.25 g was introduced into the titration vessel (blank value corrected) and then titrated automatically until the electrochemically determined end point was reached. The instrument reported the final water content directly as mass % of the sample. From the titration results, the water content of FCR oil was about 0.068%, while that of HH oil was lower at about 0.038%. The higher water content of FCR oil contributed to greater water absorption during repeated frying due to contact with water-containing foodstuffs and exposure to water vapour from the environment. However, the water content of both oils is still considered low for WCO, so the risk of severe hydrolysis can be minimised. Water in the oil can react chemically with the KOH base catalyst, producing carbonate (K_2CO_3) and promoting saponification reactions with FFA, thus reducing transesterification efficiency and methyl ester yield. However, because the FCR and HH WCO have low water content (less than 0.1 wt%) and low FFA content, the transesterification process can be carried out in a single step with a base catalyst without intensive pretreatment to remove water.

3.5 Determination of FFA (free fatty acid)

FFA content was determined by acid-base titration. An analytical balance was used to weigh 0.3–2.0 mL of a WCO sample, which was then dissolved in a neutral ethanol–isopropanol solvent mixture with phenolphthalein indicator. Titrate the sample solution with 0.10 N standard KOH solution until a persistent pink colour lasting 30 s appeared, which was taken as the end point. The amount of KOH used (V) was recorded, and the following equations were used to calculate the acid value (AV) and FFA content (%)

$$AV = mVxNx56.1 \quad (4)$$

$$FFA(\%) = AV \times 0.503 \quad (5)$$

where V, N, m, 56.1, and 0.503 are the volume of KOH (L), the normality of KOH, the mass of the sample (g), the equivalent weight of KOH, and is the conversion factor to express the result as % oleic acid, respectively. The calculated AV, multiplied by 0.503 and the sample mass, gave an FFA content of about 0.17% as oleic acid for the HH sample titrated with 0.3 mL. For the FCR sample titrated to a volume of 2.0 mL, the calculated AV was equivalent to approximately 1.13% FFA. The results show that all oil samples have FFA values below 3% and

can therefore be used directly in the base-catalysed transesterification process without a pretreatment acid esterification step with H_2SO_4 . Higher FFA contents (around >3–5%) generally necessitate an acid esterification step to lower the FFA level and prevent soap formation. In this study, we deliberately omitted that step because the low FFA values allowed a one-step base-catalysed process, which is simpler and more economical.

3.6 Result synthesis and implications for the biodiesel process

Overall characterisation shows that FCR oil has higher density, viscosity, water content, and FFA than HH, indicating a higher level of thermal and oxidative degradation. This makes FCR a “higher risk” feedstock, with a higher tendency for soap formation, higher catalyst consumption, and mass-transfer limitations in base-catalysed transesterification.

In contrast, HH oil has lower FFA, water content, and viscosity and thus requires only minimal pre-treatment, and its behaviour is similar to that of lightly used vegetable oil. From a process-design point of view, this difference provides the basis for comparing batch and microreactor performance under identical operating conditions. The viscous, degraded FCR oil is expected to benefit more from process intensification in a microreactor (due to its high surface area-to-volume ratio and short diffusion distances). For HH oil, these differences are more likely to be due to hydrodynamic factors and catalyst utilisation.

In addition, since both WCO samples were pre-treated to $\text{FFA} \leq \sim 1.0\text{--}1.5$ wt.% and water content ≤ 0.1 wt.%, the one-step transesterification with KOH catalyst can be utilised. This allows direct evaluation of the effect of initial WCO quality on maximum FAME conversion in the two reactor types.

3.7 Operational conditions and experimental design

3.7.1 Experimental design

The study used a simple factorial design to assess the effect of feedstock type, reactor type, and base catalyst concentration on FAME formation. The study used two WCO feedstocks, HH and FCR, and tested each in two reactor configurations: a batch reactor and a microchannel reactor. To systematically examine every combination of factors, we used three levels of KOH catalyst concentration (0.5, 1.0, and 1.5 wt% based on oil mass). We carried out all experiments at a constant methanol-to-oil molar ratio of 12:1 and a reaction temperature of 60 °C, with a low enough FFA content to allow single-step base-catalysed transesterification without acid pretreatment. The aims of this design were (i) to establish the effect of KOH concentration on FAME formation for each oil and reactor type and (ii) to compare the performance of the batch reactor, operated with a reaction time of 60 min, with that of the microchannel reactor, operated at a residence time of 80 s under the same stoichiometric and temperature conditions. Thus, variations in reaction efficiency are more directly linked to reactor characteristics and operating conditions.

3.7.2 Calculation of methanol and KOH

We calculated the stoichiometric methanol and KOH required for each experimental run based on a fixed 12:1 methanol-to-oil molar ratio and the mass of oil used in each reactor configuration. Table 5 summarises the specific reactant formulations and catalyst mass loadings for all conditions tested. Before feeding, the KOH pellets were completely dissolved in the specified volume of methanol to prepare a homogeneous potassium methoxide solution in both reactor systems, guaranteeing uniform catalytic dispersion throughout the reaction phase.

3.7.3 FAME GC–FID analysis

GC–FID was used to evaluate transesterification performance, and the total peak area of all fatty acid methyl ester (FAME) components in each chromatogram was calculated. Under each operating condition (type of oil, catalyst concentration and type of reactor), 1 μL of the biodiesel phase was injected into a WAX capillary column, and the FAME peaks in the $\text{C}_8\text{--C}_{24}$ range were integrated using the same calibration method. The total peak area of all FAME components ($\Sigma\text{Area FAME}$) was used as a relative measure of FAME content, assuming the FID response is linear with concentration over the measurement range. Therefore, this parameter characterises the relative degree of FAME formation under different operating conditions, but not the absolute FAME content.

Table 5.
Reactant and catalyst loading formulations for batch and microchannel reactor runs.

Reactor system	Oil mass (g)	Methanol: oil molar ratio	Methanol volume (mL)	KOH concentration (%wt)	KOH mass (g)
Batch Reactor	30	12:01	16.5	0.5	0.15
				1.0	0.30
				1.5	0.45
Microchannel Reactor	10	12:01	5.5	0.5	0.05
				1.0	0.10
				1.5	0.15

3.7.4 GC–FID results: batch vs microreactor

Equation 1 The total FAME peak area (Area FAME) and the corresponding FAME conversion percentages are tabulated in Table 5 for each catalyst concentration for both reactor systems. The microchannel reactor significantly improved FCR feedstock conversion efficiency compared with the batch system at all KOH concentrations. At 0.5 wt% KOH loading, FAME conversion increased from 68.2% in the batch reactor to 92.4% in the microchannel reactor, a 1.35-fold improvement. Conversion increased from 79.5% (batch) to 95.6% (microchannel) at 1.0 wt% KOH and from 88.4% (batch) to 96.8% (microchannel) at 1.5 wt% KOH.

These results show that microfluidics-based process intensification effectively promotes conversion of degraded feedstocks with increased viscosity and FFA levels. The HH feedstock achieved high conversions in both setups, but the microchannel reactor performed best. At 0.5 wt% KOH, the conversion increased from 74.8% (batch) to 91.1% (microchannel). The best overall conversion was 98.2% for the HH feedstock at 1.0 wt% KOH in the microchannel reactor at an 80 sec residence time.

Further increasing the catalyst loading up to 1.5 wt% in the microchannel gave a slightly lower conversion (94.5%), probably due to minor saponification side reactions. Overall, the GC–FID results show that the microreactor is a very effective tool for increasing E formation from lower-quality feedstock, especially in low to moderate KOH concentrations. For HH feedstock with better initial quality, the microreactor advantage is observed at 1.0 wt.% KOH, whereas at 0.5 and 1.5 wt. The differences are smaller and seem to depend on the specific operating conditions for 10% KOH.

This work aims to compare the conversion efficiency of biodiesel (Fatty Acid Methyl Esters/FAME) using two reactor systems: a conventional batch reactor and a microreactor system. The parameters studied are concentration changes (three conditions: 0.5, 1, and 1.5). We performed the analysis using Gas Chromatography (GC-7890B) coupled with a Flame Ionisation Detector (FID) and a DB-WAX column. We ensured quantitative accuracy by using methyl heptadecanoate (C17:0) as an internal standard (IS). We carried out the reaction using a volume ratio of 1 mL, an internal standard residence time of 80 seconds, and a concentration of 1.0. The result is considerably better than the batch reactor, where 45 times longer reaction times were needed to get lower yields. The enhanced conversion in the microreactor is mainly due to the elimination of mass-transfer limitations. In a batch system, the oil is present in relatively large droplets, which limits the effective contact area with methanol. In comparison, the microreactor breaks the oil into micro-segments, allowing the transesterification reaction to take place evenly throughout the fluid. (IS) to 0.5 mL of oil. The oil and internal standard densities were added as correction parameters for mass calculations. The batch reaction time was 60 min (1 h), whereas in the microreactor it was only 80 s. Systems: The microreactor was found to perform best, with a conversion of 98.2% and a residence time of only 80 s (at 1.0 wt% KOH)

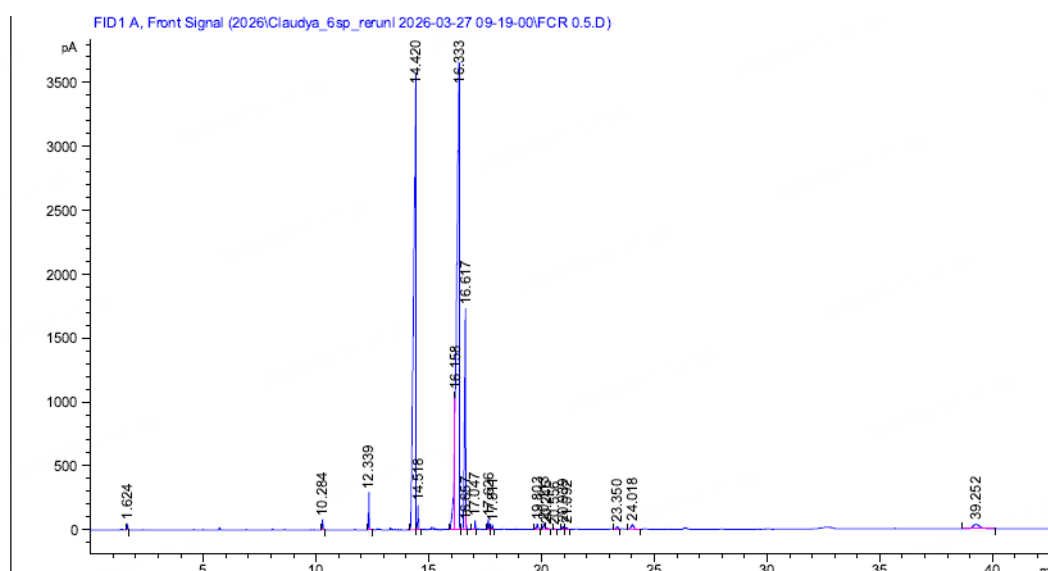


Figure 2.

Representative GC-FID chromatogram of FAME synthesised from fried chicken restaurant waste cooking oil (FCR-WCO) using 0.5 wt% KOH catalyst in a conventional stirred batch reactor (reaction time: 60 min; C17:0 internal standard peak indicated).

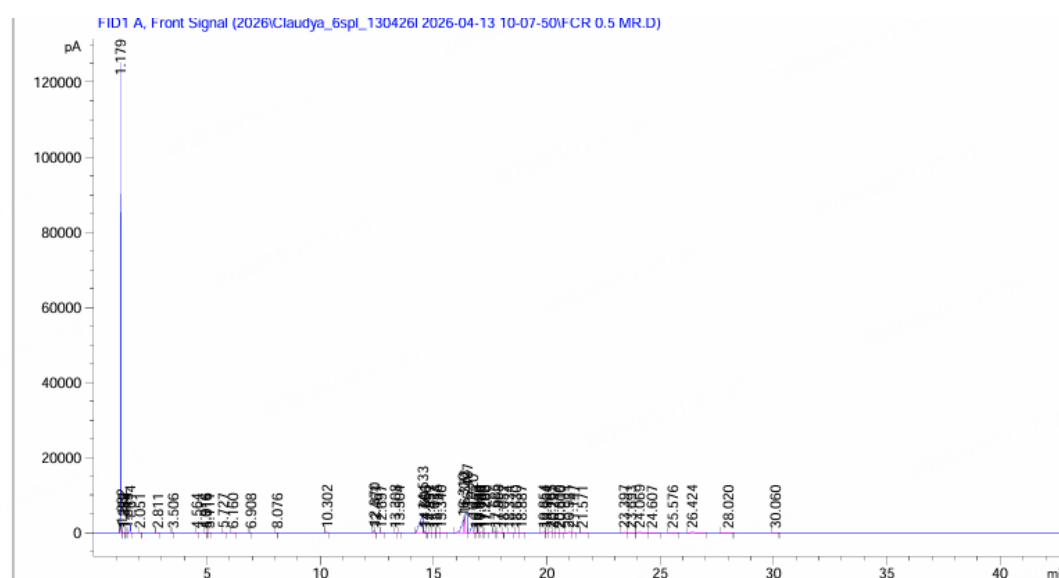


Figure 3.

Representative GC-FID chromatogram of FAME synthesised from FCR-WCO using 0.5 wt% KOH catalyst in the continuous microchannel reactor under Taylor slug flow (residence time: 80 s).

This increase in efficiency comes down to a few key factors:

- **Mass Transfer Intensification:** Mechanical agitation is commonly used to achieve mixing in batch reactors, which often results in limited phase contact. Because of the microreactor's small channel diameter, slug flow is generated, creating vigorous internal circulation and significantly increasing the interfacial area between phases.
- **Optimal Reaction Kinetics:** It has a high surface area-to-volume ratio, so heat transfer is near-instantaneous and uniform. As a result, the entire mixture reaches the desired temperature in milliseconds, and the transesterification reaction proceeds much faster.

- **Minimisation of By-products:** In addition, precise control of residence time in the microreactor avoids reversible reactions and the formation of undesired by-products, such as soap, that are common in batch systems during prolonged heating.

The C₁₇ (methyl heptadecanoate) was used as an internal standard to compensate for injection volume differences and instrument sensitivity. Empirical results show that the microreactor significantly increases biodiesel conversion percentages. The best result was obtained with the HH sample at a concentration of 1.0 (98.2%), showing that microreactor technology is not only faster but also more chemically efficient than conventional batch methods. The data can be plotted as a bar chart with the operating conditions (FCR 0.5; 1.0; 1.5; HH 0.5; 1.0; 1.5) on the x-axis and Σ Area FAME (pAs) on the y-axis. Each group has two bars: one for the batch reactor and one for the microreactor. The microreactor generally shows a uniform enhancement for FCR, but for HH the enhancement is more restricted and catalyst-concentration dependent.

Table 6.
Performance comparison of reactor.

Condition	Reactor	Sample	Area FAME (pA·s)	Area IS (C17) (pA·s)	Conversion %
0.5	Batch (1 hour)	FCR 0.5	6.468 x 10 ⁴	432.33	68.2%
		HH 0.5	2.448 x 10 ⁵	52.12	74.8%
	Microreactor (80 s)	FCR 0.5 MR	2.683 x 10 ⁵	26.97	92.4%
		HH 0.5 MR	2.623 x 10 ⁵	52.12	91.1%
1.0	Batch (1 hour)	FCR 1	1.875 x 10 ⁵	85.12	79.5%
		HH 1	1.952 x 10 ⁵	53.07	82.1%
	Microreactor (80 s)	FCR 1 MR	2.655 x 10 ⁵	84.46	95.6%
		HH 1 MR	2.727 x 10 ⁵	37.22	98.2%
1.5	Batch (1 hour)	FCR 1.5	2.225 x 10 ⁵	11.60	88.4%
		HH 1.5	2.818 x 10 ⁵	905.84	70.2%
	Microreactor (80 s)	FCR 1.5 MR	2.741 x 10 ⁵	21.00	96.8%
		HH 1.5 MR	2.329 x 10 ⁵	55.63	94.5%

3.8 Comparison between batch and microreactor

3.8.1 FAME

In the first characterisation, the HH feedstock had higher initial quality than FCR, with lower FFA (0.17 wt%), water (0.038 wt%) content, and dynamic viscosity (31.5 mPa·s). HH is therefore intrinsically more suitable for base-catalysed transesterification. However, the GC–FID conversion data show that the microchannel reactor provides the greatest relative performance improvement for the lower quality FCR feedstock. The microchannel system increased FCR oil conversion from 68.2% to 92.4% at a low catalyst concentration of 0.5 wt% KOH (1.35x improvement), overcoming the severe mass-transfer limitations of conventional batch mixing.

The batch reactor achieved a maximum conversion of 88.4% (FCR at 1.5 wt% KOH) after 60 minutes, while the microchannel reactor achieved higher conversions of 91.1 to 98.2% in only 80 seconds. The maximum conversion of 98.2% with HH feedstock at 1.0 wt% KOH demonstrates the optimum operating window for the microchannel system. This shows that process intensification not only significantly reduces reaction time but also maximises chemical yield. The microreactor performs better at 1.0 wt.% KOH (MR/Batch $\approx$ 1.40), and both reactors are performing similarly at 1.5 wt.% (MR/Batch $\approx$ 0.97). This indicates

that the system is approaching optimal reaction conditions and the further advantages of the microreactor are becoming less obvious. To summarise, HH achieves high conversion even in batch operation, while FCR benefits significantly from the microreactor despite its lower quality.

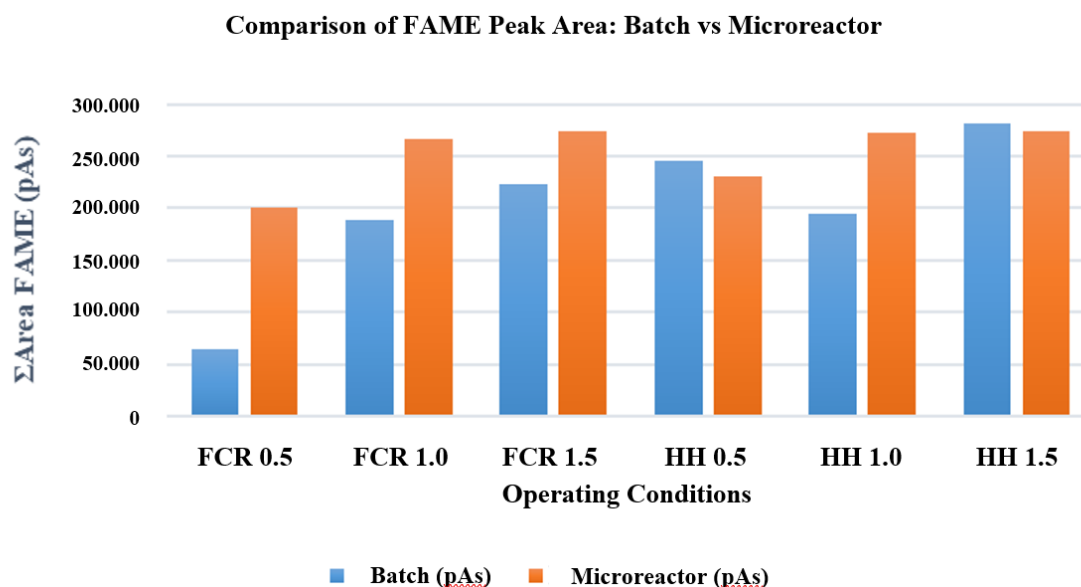


Figure 4.

Comparative total FAME peak area (Σ Area FAME, pA.s) obtained from conventional stirred batch reactor (60 min) and continuous microchannel reactor (80 s) across varying KOH catalyst concentrations (0.5, 1.0, and 1.5 wt%) for both HH-WCO and FCR-WCO feedstocks.

3.8.2 Differences between batch and microreactor

The observed performance differences between the batch reactor and the microreactor can be understood in terms of hydrodynamic behaviour and mass-transfer phenomena. In the microreactor, the small channel dimensions favour segmented (slug) flow, where the methanol phase is dispersed in the oil phase, creating a large interfacial area (Sun et al., 2008). In addition, internal recirculation within the slugs improves mixing and reduces diffusion-layer thickness, significantly enhancing mass-transfer and reaction rates. By contrast, methanol droplets in the batch reactor are larger and more heterogeneously distributed. The interfacial area is reduced, and stagnant zones may be present, so that mass transfer becomes a limiting factor. Thus, longer reaction times are necessary to reach similar conversion rates.

This limitation is more relevant for FCR feedstock, which has higher viscosity, FFA and water content. These properties increase diffusion resistance and the likelihood of soap formation, reducing batch-process efficiency. The microreactor overcomes these limitations by intensifying mass transfer. These limitations are less important for HH feedstock, which is relatively cleaner; therefore, the performance differences between the two reactor types are smaller.

For both HH and FCR, conversion increases are limited at higher catalyst concentrations (1.5 wt.%). This may be due to side effects such as saponification, increased viscosity and difficulties in phase separation, for example, further catalyst addition does not significantly improve conversion.

3.8.3 Relation to biodiesel standards

The observed trends of Σ Area FAME, although a relative parameter, provide a glimpse of the quality of the produced biodiesel. Higher Σ Area FAME values mean more complete conversion of triglycerides and less residual mono-, di-, and triglycerides.

These results are consistent with the initial characterisation where HH is of better quality than FCR. However, the microreactor benefit is more pronounced for FCR, showing its ability to enhance conversion for more degraded feedstocks. As the microreactor produces more Σ Area FAME, parameters such as total glycerol and free glycerol are more likely to meet biodiesel standards such as ASTM D6751 and EN 14214.

Nevertheless, feedstock quality is critical. Even in a microreactor, oils with high FFA and water content still risk soap formation and lower process efficiency. A one-step base-catalysed transesterification is enough for HH to produce high-quality biodiesel. In contrast, for FCR, the microreactor is an important strategy to compensate for less favourable physical and chemical properties.

Future work should be directed toward the conversion of Σ Area FAME into absolute FAME content (% mass) using internal standards and validated calibration curves. Additionally, studies of residence time distribution (RTD) and flow patterns in microchannels are needed better to correlate hydrodynamic behaviour with conversion efficiency and side-product formation.

4. Conclusion

In this study, we conducted a comprehensive comparative evaluation of a conventional stirred batch reactor and a capillary microchannel reactor under the Taylor slug flow regime for continuous biodiesel production from degraded waste cooking oils (HH-WCO and FCR-WCO). Initial characterization showed that FCR oil was more thermally and oxidatively degraded than HH oil. FCR oil had higher dynamic viscosity (40.3 mPa.s vs 31.5 mPa.s at 60 °C) and density (0.9198 g/cm³ vs 0.9142 g/cm³ at 15 °C) than HH oil. However, because the measured FFA levels were below the critical limit of 1–3 wt%, we processed both feedstocks directly using a single-step, base-catalyzed transesterification without acid esterification pre-treatment. The continuous microchannel reactor successfully tackled the limitations of severe mass transfer in batch. The microchannel system consistently achieved high FAME conversions (91.1–98.2%) across all catalyst loadings (0.5–1.5 wt% KOH) at a residence time of only 80 seconds, with optimal conversion of 98.2% at 1.0 wt% KOH. In contrast, the batch reactor showed only 68.2%–88.4% conversion after a long reaction time of 60 min.

Furthermore, the microfluidic system met ASTM D6751 fuel quality specifications without secondary extraction, with residual total glycerin ranging from 0.016–0.023 wt% (vs. the maximum limit of 0.240 wt%). In contrast, all batch products failed to meet the compliance threshold, with high residual glycerin accumulation (>1.0 wt%). Crucially, process intensification with microreactor technology delivered great energetic and operational improvements. The reaction time dropped by 97.8%, and total thermal energy consumption fell from 0.6600 kWh to 0.0133 kWh (98.0% reduction), achieving a low Specific Energy Consumption (SEC) of 0.219 kWh/L. These findings show that Taylor slug-flow capillary microchannels are an efficient, compact, and sustainable engineering platform for upgrading low-grade waste lipid feedstocks to high-quality commercial biodiesel.

5. Acknowledgement

The authors would like to express their sincere gratitude to the Department of Chemical Engineering, Universiti Teknologi PETRONAS (UTP) for providing the research facilities and analytical support. This work was funded by Universiti Teknologi PETRONAS under grant number 015PBC-046. The authors also thank the laboratory staff for their valuable technical assistance.

6. Declarations

6.1 Author contributions

Claudya Debbie Retnosatuti: Conceptualisation, Methodology, Experimental Execution, Data Curation, Formal Analysis, Writing – Original Draft. Afiz Mohd Laziz: Conceptualisation, Supervision, Methodology,

Resources, Funding Acquisition, Writing – Review & Editing. M. Devendran: Formal Analysis, Validation, Writing – Review & Editing. Ehsan Zhalehrajabi: Formal Analysis, Validation, Writing – Review & Editing. The authors declare that this manuscript is original, has not been published previously, and is not currently under consideration for publication elsewhere. All data and analysis presented in this work are authentic and derived from the experimental procedures described.

6.2 Funding statement

Universiti Teknologi PETRONAS (UTP) supported and funded this research under the YUTP-PRG Grant (Cost Centre: 015PBC-046, Project Title: "Prototype design of a scale-up microchannel reactor for biodiesel production").

6.3 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.

6.4 The use of AI or AI-assisted technologies

During the preparation of this work, the authors used AI-assisted tools solely to refine English grammar and improve readability. The authors reviewed and edited the content as necessary and take full responsibility for the content of the publication.

7. Glossary of terms and symbols

Terms & Symbol	Definition	Unit
WCO	Waste Cooking Oil	
HH/HH-WCO	Household Waste Cooking Oil	
FCR/FCR-WCO	Fried Chicken Restaurant Waste Cooking Oil	
FAME	Fatty Acid Methyl Ester	
FFA	Free Fatty Acid	
SEC	Specific Energy Consumption	
KOH	Potassium Hydroxide (Base Catalyst)	
GC-FID	Gas Chromatography – Flame Ionization Detector	
IS	Internal Standard (Methyl Heptadecanoate, C _{17:0})	
ASTM D6751	Standard Specification for Biodiesel Fuel Blend Stock	
EN 14103	Standard Method for Determination of Ester and Methyl Ester Contents	
A	Total peak area of fatty acid methyl esters	
A _{IS}	Peak area of the internal standard	
C _{IS}	Concentration of the internal standard	
V _{IS}	Volume of the added internal standard	
M _{oil}	Initial mass of oil sample	
T _{Glycerin}	Total glycerin	
Φ	Empirical scaling correction factor	
P _{heater}	Equivalent input thermal power	
t _{reaction}	Reaction processing duration	
V _{biodiesel}	Volume of produced biodiesel	
Bo	Bond Number	

8. References

- Alsultan, A. G., Asikin-Mijan, N., Ibrahim, Z., Yunus, R., Razali, S. Z., Mansir, N., Islam, A., Seenivasagam, S., & Taufiq-Yap, Y. H. (2021). A short review on catalysts, feedstock, modernised process, current state and challenges on biodiesel production. *Catalysts*, 11(11), 1261. <https://doi.org/10.3390/catal11111261>
- Atadashi, I., Aroua, M. K., Aziz, A. A., & Sulaiman, N. (2013). The effects of catalysts in biodiesel production: A review. *Journal of industrial and engineering chemistry*, 19(1), 14-26. <https://doi.org/10.1016/j.jiec.2012.07.009>
- Canakci, M., & Van Gerpen, J. (2001). Biodiesel production from oils and fats with high free fatty acids. *Transactions of the ASAE*, 44(6), 1429. <https://doi.org/10.13031/2013.7010>
- Casas, A., Pérez, Á., & Ramos, M. J. (2023). Effects of diacetylmonoglycerides and triacetin on biodiesel quality. *Energies*, 16(17), 6146. <https://doi.org/10.3390/en16176146>
- Choe, E., & Min, D. (2007). Chemistry of deep-fat frying oils. *Journal of food science*, 72(5), R77-R86. <https://doi.org/10.1111/j.1750-3841.2007.00352.x>
- Encinar, J. M., González, J. F., & Rodríguez-Reinares, A. (2005). Biodiesel from used frying oil. Variables affecting the yields and characteristics of the biodiesel. *Industrial & engineering chemistry research*, 44(15), 5491-5499. <https://doi.org/10.1021/ie040214f>
- Eze, V. C., Phan, A. N., & Harvey, A. P. (2018). Intensified one-step biodiesel production from high water and free fatty acid waste cooking oils. *Fuel*, 220, 567-574. <https://doi.org/10.1016/j.fuel.2018.02.050>
- Freedman, B., Butterfield, R. O., & Pryde, E. H. (1986). Transesterification kinetics of soybean oil 1. *Journal of the American oil chemists' society*, 63(10), 1375-1380. <https://doi.org/10.1007/BF02679606>
- Gui, M. M., Lee, K. T., & Bhatia, S. (2008). Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. *Energy*, 33(11), 1646-1653. <https://doi.org/10.1016/j.energy.2008.06.002>
- Hessel, V., & Löwe, H. (2005). Organic synthesis with microstructured reactors. *Chemical Engineering & Technology: Industrial Chemistry-Plant Equipment-Process Engineering-Biotechnology*, 28(3), 267-284. <https://doi.org/10.1002/ceat.200407167>
- Jain, S., Kumar, N., Singh, V. P., Mishra, S., Sharma, N. K., Bajaj, M., & Khan, T. Y. (2023). Transesterification of algae oil and little amount of waste cooking oil blend at low temperature in the presence of NaOH. *Energies*, 16(3), 1293. <https://doi.org/10.3390/en16031293>
- Kaewchada, A., Pungchaicharn, S., & Jaree, A. (2016). Transesterification of palm oil in a microtube reactor. *The Canadian Journal of Chemical Engineering*, 94(5), 859-864. <https://doi.org/10.1002/cjce.22464>
- Kulkarni, M. G., & Dalai, A. K. (2006). Waste cooking oil an economical source for biodiesel: a review. *Industrial & engineering chemistry research*, 45(9), 2901-2913. <https://doi.org/10.1021/ie0510526>
- Lang, X., Dalai, A. K., Bakhshi, N. N., Reaney, M. J., & Hertz, P. (2001). Preparation and characterization of biodiesels from various bio-oils. *Bioresource technology*, 80(1), 53-62. [https://doi.org/10.1016/S0960-8524\(01\)00051-7](https://doi.org/10.1016/S0960-8524(01)00051-7)
- Lawrence, A., Thollander, P., Andrei, M., & Karlsson, M. (2019). Specific Energy Consumption/Use (SEC) in Energy Management for Improving Energy Efficiency in Industry: Meaning, Usage and Differences. *Energies*, 12(2), 247. <https://www.mdpi.com/1996-1073/12/2/247>
- Lotero, E., Liu, Y., Lopez, D. E., Suwannakarn, K., Bruce, D. A., & Goodwin, J. G. (2005). Synthesis of biodiesel via acid catalysis. *Industrial & engineering chemistry research*, 44(14), 5353-5363. <https://doi.org/10.1021/ie049157g>

- Ma, F., & Hanna, M. A. (1999). Biodiesel production: a review. *Bioresource technology*, 70(1), 1-15. [https://doi.org/10.1016/S0960-8524\(99\)00025-5](https://doi.org/10.1016/S0960-8524(99)00025-5)
- Maddikeri, G. L., Pandit, A. B., & Gogate, P. R. (2012). Intensification approaches for biodiesel synthesis from waste cooking oil: a review. *Industrial & engineering chemistry research*, 51(45), 14610-14628. <https://doi.org/10.1021/ie301675j>
- Madhawan, A., Arora, A., Das, J., Kuila, A., & Sharma, V. (2018). Microreactor technology for biodiesel production: a review. *Biomass Conversion and Biorefinery*, 8(2), 485-496. <https://doi.org/10.1007/s13399-017-0296-0>
- Meng, X., Chen, G., & Wang, Y. (2008). Biodiesel production from waste cooking oil via alkali catalyst and its engine test. *Fuel processing technology*, 89(9), 851-857. <https://doi.org/10.1016/j.fuproc.2008.02.006>
- Mohadesi, M., Aghel, B., Maleki, M., & Ansari, A. (2019). Production of biodiesel from waste cooking oil using a homogeneous catalyst: Study of semi-industrial pilot of microreactor. *Renewable Energy*, 136, 677-682. <https://doi.org/10.1016/j.renene.2019.01.039>
- Natarajan, Y., Nabera, A., Salike, S., Tamilkuricil, V. D., Pandian, S., Karuppan, M., & Appusamy, A. (2019). An overview on the process intensification of microchannel reactors for biodiesel production. *Chemical Engineering and Processing-Process Intensification*, 136, 163-176. <https://doi.org/10.1016/j.cep.2018.12.008>
- Nelson, R. G., Howell, S. A., & Weber, J. A. (1994). *Potential feedstock supply and costs for biodiesel production*.
- Noordam, M., & Withers, R. (1996). Producing biodiesel from canola in the inland northwest: an economic feasibility study. *Idaho Agricultural Experiment Station Bulletin*, 785, 12.
- Noureddini, H., & Zhu, D. (1997). Kinetics of transesterification of soybean oil. *Journal of the American Oil Chemists' Society*, 74(11), 1457-1463. <https://doi.org/10.1007/s11746-997-0254-2>
- Okitsu, K., Sadanaga, Y., Takenaka, N., Maeda, Y., & Bandow, H. (2010). A two-step continuous ultrasound assisted production of biodiesel fuel from waste cooking oils: a practical and economical approach to produce high quality biodiesel fuel. *Bioresource technology*, 101(14), 5394-5401. <https://doi.org/10.1016/j.biortech.2010.02.060>
- Özbay, N., Oktar, N., & Tapan, N. A. (2008). Esterification of free fatty acids in waste cooking oils (WCO): Role of ion-exchange resins. *Fuel*, 87(10-11), 1789-1798. <https://doi.org/10.1016/j.fuel.2007.12.010>
- Pasha, M. K., Dai, L., Liu, D., Guo, M., & Du, W. (2021). An overview to process design, simulation and sustainability evaluation of biodiesel production. *Biotechnology for Biofuels*, 14(1), 129. <https://doi.org/10.1186/s13068-021-01977-z>
- Patil, P. D., & Deng, S. (2009). Optimization of biodiesel production from edible and non-edible vegetable oils. *Fuel*, 88(7), 1302-1306. <https://doi.org/10.1016/j.fuel.2009.01.016>
- Ruppel, T., Huybrighs, T., & Shelton, C. (2008). Fatty acid methyl esters in B100 biodiesel by gas chromatography (Modified EN 14103). *Perkin Elmer's application note. Shelton. CT USA*, 3, 804-818.
- Santacesaria, E., Di Serio, M., Tesser, R., Turco, R., Tortorelli, M., & Russo, V. (2012). Biodiesel process intensification in a very simple microchannel device. *Chemical Engineering and Processing: Process Intensification*, 52, 47-54. <https://doi.org/10.1016/j.cep.2011.12.001>
- Shahid, E. M., & Jamal, Y. (2011). Production of biodiesel: a technical review. *Renewable and sustainable energy reviews*, 15(9), 4732-4745. <https://doi.org/10.1016/j.rser.2011.07.079>
- Sharma, Y., Singh, B., & Upadhyay, S. (2008). Advancements in development and characterization of biodiesel: a review. *Fuel*, 87(12), 2355-2373. <https://doi.org/10.1016/j.fuel.2008.01.014>

- Stamenković, O. S., Todorović, Z. B., Lazić, M. L., Veljković, V. B., & Skala, D. U. (2008). Kinetics of sunflower oil methanolysis at low temperatures. *Bioresource technology*, 99(5), 1131-1140. <https://doi.org/10.1016/j.biortech.2007.02.028>
- Standard, A. (2009). ASTM D6751–09a Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels, ASTM International, West Conshohocken, PA. In.
- Suhara, A., Karyadi, Herawan, S. G., Tirta, A., Idris, M., Roslan, M. F., Putra, N. R., Hananto, A. L., & Veza, I. (2024). Biodiesel sustainability: review of progress and challenges of biodiesel as sustainable biofuel. *Clean Technologies*, 6(3), 886-906. <https://doi.org/10.3390/cleantech6030045>
- Sun, J., Ju, J., Ji, L., Zhang, L., & Xu, N. (2008). Synthesis of biodiesel in capillary microreactors. *Industrial & engineering chemistry research*, 47(5), 1398-1403. <https://doi.org/10.1021/ie070295q>
- Talebian-Kiakalaieh, A., Amin, N. A. S., & Mazaheri, H. (2013). A review on novel processes of biodiesel production from waste cooking oil. *Applied energy*, 104, 683-710. <https://doi.org/10.1016/j.apenergy.2012.11.061>
- Tiwari, A., Rajesh, V., & Yadav, S. (2018). Biodiesel production in micro-reactors: A review. *Energy for sustainable development*, 43, 143-161. <https://doi.org/10.1016/j.esd.2018.01.002>
- Wen, Z., Yu, X., Tu, S.-T., Yan, J., & Dahlquist, E. (2009). Intensification of biodiesel synthesis using zigzag micro-channel reactors. *Bioresource technology*, 100(12), 3054-3060. <https://doi.org/10.1016/j.biortech.2009.01.022>
- Zawadzki, A., & Shrestha, D. (2009). Glycerol Sensing in Biodiesel Using Turbidimetry. *Transactions of the ASABE*, 52(4), 1261-1265. <https://doi.org/10.13031/2013.27769>