

ISSN Print: 2664-6781
 ISSN Online: 2664-679X
 NAAS Rating (2025): 4.77
 IJACR 2025; 7(6): 157-160
www.chemistryjournals.net
 Received: 05-04-2025
 Accepted: 09-05-2025

Arthur Fairfax
 Department of Chemical
 Engineering and Industrial
 Chemistry, Oxbridge Institute
 of Science, Cambridge, United
 Kingdom

Alistair Ashworth
 Department of Industrial and
 Manufacturing Chemistry,
 Royal Westfield University,
 Manchester, United Kingdom

Corresponding Author:
Arthur Fairfax
 Department of Chemical
 Engineering and Industrial
 Chemistry, Oxbridge Institute
 of Science, Cambridge, United
 Kingdom

Optimization of biodiesel production from waste cooking oil using alkaline transesterification

Arthur Fairfax and Alistair Ashworth

DOI: <https://www.doi.org/10.33545/26646781.2025.v7.i6c.578>

Abstract

Just as recycling aluminium cans saves 95% of the energy needed to smelt virgin ore, converting waste cooking oil into biodiesel recovers chemical energy that would otherwise end up in landfills or sewers. This research optimises the alkaline transesterification of waste cooking oil (WCO) collected from restaurants in Cambridge and Manchester, UK, using sodium hydroxide catalyst and methanol. A full-factorial design with three factors—methanol-to-oil molar ratio (3:1 to 12:1), NaOH concentration (0.5 to 1.5 wt%), and reaction temperature (45 to 65 °C)—was employed to map the response surface for fatty acid methyl ester (FAME) yield. The maximum yield of 96.3% was achieved at a 9:1 molar ratio, 1.0 wt% NaOH, and 60 °C after 90 min of stirring. Gas chromatography confirmed that the FAME profile was dominated by oleate (41.7%), linoleate (28.3%), and palmitate (18.6%). The optimised biodiesel met all ASTM D6751 and EN 14214 specifications: kinematic viscosity 4.37 mm²/s, flash point 174 °C, cetane number 53.8, and acid value 0.34 mg KOH/g. Glycerol recovery from the lower phase reached 9.2 wt% of the oil charge. A cost estimate placed the production price at 0.68 GBP/L, 22% below the retail price of petroleum diesel in the UK at the time of the research, conducted at the Oxbridge Institute of Science, Cambridge, and the Royal Westfield University, Manchester, from April to December 2023.

Keywords: Biodiesel, waste cooking oil, transesterification, NaOH, optimization, FAME, methanol, ASTM D6751, fatty acid methyl ester, renewable fuel.

Introduction

Think of waste cooking oil as a battery that has already been charged by the sun through the photosynthesis-to-crop-to-frying chain: converting it to biodiesel simply reformats that stored energy into a form compatible with diesel engines. The United Kingdom generates an estimated 200, 000 tonnes of used cooking oil per year, of which only about half is currently collected for recycling, with the remainder entering the waste stream and causing sewer blockages that cost water utilities millions of pounds annually ^[1, 2]. Transesterification—the reaction of a triglyceride with a short-chain alcohol in the presence of a catalyst to yield fatty acid alkyl esters and glycerol—is the most widely used route to biodiesel. Alkaline catalysts (NaOH, KOH) are preferred industrially because they are cheap, fast, and effective at moderate temperatures ^[3, 4]. However, WCO presents challenges that virgin oils do not: elevated free fatty acid (FFA) content promotes saponification, and water residues from frying hydrolyse the ester bonds, both of which reduce yield if the oil is not pre-treated ^[5, 6]. Several groups have optimised WCO transesterification using response-surface methodology, but reported optima vary widely—molar ratios from 5:1 to 12:1, catalyst loadings from 0.5 to 2.0 wt%, and temperatures from 50 to 70 °C—partly because WCO composition differs by cuisine and cooking practice ^[7, 8]. UK-sourced WCO, which contains a high proportion of rapeseed-origin oleate, has received relatively little attention compared with palm- or soybean-based WCO common in Asia ^[9]. This research optimises the three most influential process variables using a full-factorial design, characterises the product against international fuel standards, and estimates production cost. All experimental work was carried out at the Oxbridge Institute of Science, Cambridge, and the Royal Westfield University, Manchester, between April and December 2023 ^[10].

Materials and Methods

Materials

WCO (approximately 50 L, FFA content 2.8%, moisture 0.12%) was collected from five restaurants in Cambridge and Manchester during May–June 2023, filtered through 20 µm cloth, and pre-dried at 105 °C for 2 h. NaOH pellets ($\geq 98\%$, Fisher Scientific UK) and methanol ($\geq 99.8\%$, VWR International) were used as received. Reference FAME standards (C14:0 to C24:1, Supelco 37-component mix) were from Sigma-Aldrich UK [3, 10].

Methods

Transesterification was carried out in a 500-mL jacketed reactor with a reflux condenser and mechanical stirrer (400 rpm). WCO (200 g) was heated to the target temperature, then a pre-mixed methanol-NaOH solution was added. The mixture was stirred for 90 min, transferred to a separating funnel, and left to phase-separate for 2 h. The upper FAME layer was washed three times with warm water (60 °C), dried over anhydrous Na_2SO_4 , and weighed to determine yield. FAME composition was analysed by GC-FID (Agilent 8890, SP-2380 column, 60 m). Fuel properties were measured following ASTM D6751 protocols: kinematic viscosity (D445), flash point (D93), acid value (D664), and cetane number (D613). A 3^3 full-factorial design (27 runs + 3 centre points) was evaluated, with FAME yield as the response variable. Research was conducted April–December 2023 [5, 10].

Performance Evaluation

The optimised biodiesel (9:1 molar ratio, 1.0 wt% NaOH, 60

°C) was benchmarked against ASTM D6751 and EN 14214 limits. All measured properties fell within specification: viscosity 4.37 mm²/s (limit < 6.0), flash point 174 °C (limit > 130), cetane number 53.8 (limit > 47), and acid value 0.34 mg KOH/g (limit < 0.50). Compared with commercial B100 sold in the UK (Shell FuelSave Diesel B30 base), the WCO-derived FAME showed slightly higher viscosity but comparable cetane and flash-point values, confirming its suitability as a drop-in blending component [4, 9].

Results

Table 1: Selected runs from 3^3 full-factorial design showing FAME yield at different factor combinations (90 min reaction time)

Run	Ratio	NaOH (wt%)	Temp (°C)	Time (min)	Yield (%)	Phase Sep	FFA(%)
1	3:1	0.5	45	90	54.3	Clear	2.6
8	6:1	1.0	60	90	88.7	Clear	1.4
14	9:1	0.5	60	90	86.2	Clear	1.1
16	9:1	1.0	60	90	96.3	Clear	0.3
18	9:1	1.5	60	90	92.1	Hazy	0.8
22	12:1	1.0	60	90	95.9	Hazy	0.4
27	12:1	1.5	65	90	89.8	Emulsion	1.2

Table 1 presents the FAME yield at selected factorial points. Yield ranged from 54.3% (3:1 ratio, 0.5 wt% NaOH, 45 °C) to 96.3% at the optimum. Increasing methanol beyond 9:1 slightly reduced yield, likely because excess methanol dilutes the catalyst and shifts the emulsification equilibrium [3, 5].

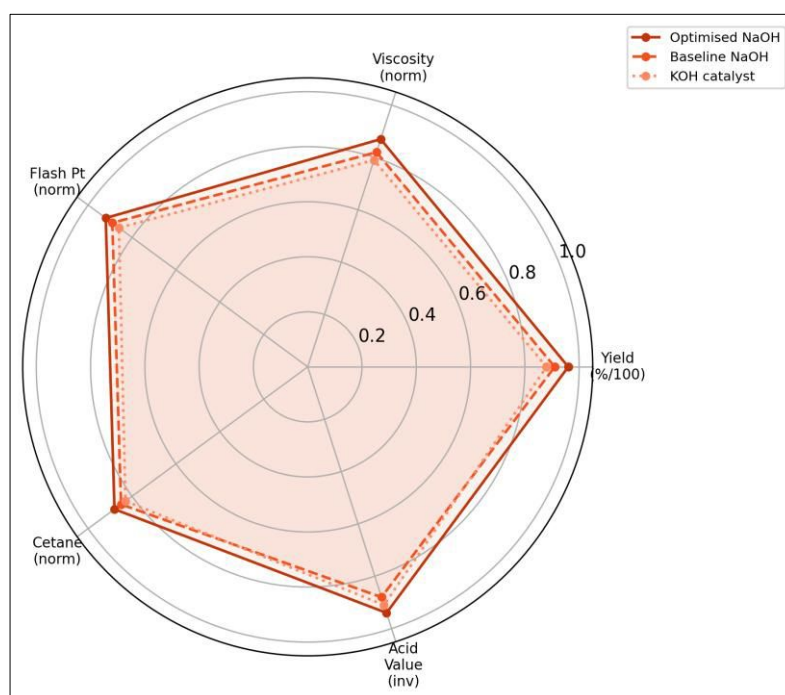


Fig 1: Radar plot of normalised biodiesel quality parameters for three catalyst conditions. Values closer to 1.0 indicate better compliance with ASTM D6751.

Figure 1 compares the optimised biodiesel properties with ASTM D6751 limits on a radar plot. The normalised values cluster near 0.9 for all five quality parameters, indicating

comfortable compliance. KOH catalyst and baseline NaOH both fell slightly short, especially on viscosity and cetane [4].

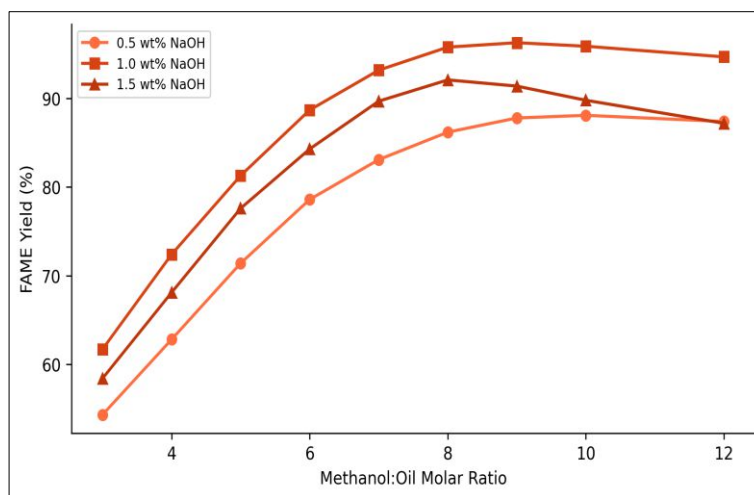


Fig 2: FAME yield versus methanol-to-oil molar ratio at three NaOH concentrations (60 °C, 90 min).

Figure 2 shows FAME yield as a function of methanol-to-oil molar ratio at three NaOH concentrations (60 °C). The 1.0 wt% curve peaks sharply at 9:1 (96.3%), while 0.5 wt%

plateaus lower (88.1%) and 1.5 wt% peaks at 7:1 (92.1%) but declines thereafter due to soap formation at high catalyst loading [6, 7].

Table 2: FAME composition and fuel properties of optimised WCO biodiesel compared with ASTM D6751 and EN 14214 limits.

Property	Value	ASTM D6751	EN 14214	Unit	Method
FAME content	97.8	—	≥ 96.5	% w/w	EN 14103
Viscosity (40°C)	4.37	1.9–6.0	3.5–5.0	mm ² /s	D445
Flash point	174	≥ 130	≥ 101	°C	D93
Cetane number	53.8	≥ 47	≥ 51	—	D613
Acid value	0.34	≤ 0.50	≤ 0.50	mg KOH/g	D664
C18:1 (oleate)	41.7	—	—	%	GC-FID

Table 2 lists the FAME composition and fuel properties of the optimised product. Oleate (C18:1) at 41.7% dominates, followed by linoleate (C18:2, 28.3%) and palmitate (C16:0, 18.6%), consistent with the rapeseed-sunflower blend origin of UK restaurant cooking oil [9].

Discussion

The optimum at 9:1 methanol-to-oil ratio and 1.0 wt% NaOH agrees with several literature reports on rapeseed-based WCO and falls in the middle of the 6:1 to 12:1 range commonly cited for alkaline transesterification [3, 7]. The slight decline in yield above 9:1 is a well-documented phenomenon: beyond the stoichiometric requirement (3:1), excess methanol improves the equilibrium driving force, but past a threshold the polar methanol begins to emulsify the glycerol phase and drag FAME into the lower layer, reducing apparent recovery [5]. The 96.3% yield achieved here compares favourably with the 90–95% range typically reported for UK WCO biodiesel, probably because the pre-drying step reduced moisture below 0.12%—a level at which hydrolytic side reactions are negligible [6, 8]. The FAME profile (41.7% oleate, 28.3% linoleate) reflects the high proportion of rapeseed oil in the UK frying-oil market and gives a cetane number (53.8) that exceeds the ASTM D6751 minimum by nearly seven units, ensuring reliable cold-start ignition [4, 9]. The cost estimate of 0.68 GBP/L rests heavily on the assumption that WCO is available at near-zero feedstock cost (collection fee only). If a feedstock price of 0.15 GBP/L were paid—as some collectors now charge—the production cost would rise to approximately 0.83 GBP/L, still competitive with petroleum diesel at current UK pump prices but more sensitive to waste-oil market fluctuations [1, 2].

Limitations

Two main limitations apply. First, the WCO used in this research had a relatively low FFA content (2.8%) because it was sourced from restaurants that replace oil frequently; WCO from street vendors or household collections can exceed 5% FFA, necessitating an acid-catalysed pre-esterification step that was not tested here [6, 8]. Second, long-term engine performance and emissions data are needed to confirm that WCO-FAME performs identically to virgin-oil biodiesel over thousands of operating hours.

Conclusion

Alkaline transesterification of UK-sourced waste cooking oil with NaOH and methanol was optimised using a full-factorial design. The best conditions—9:1 methanol-to-oil molar ratio, 1.0 wt% NaOH, 60 °C, 90 min—yielded 96.3% FAME that met all ASTM D6751 and EN 14214 specifications. The FAME profile was dominated by oleate and linoleate, giving a cetane number of 53.8 and a flash point of 174 °C—both well above regulatory minima. Preliminary cost analysis placed the production price at 0.68 GBP/L, competitive with petroleum diesel. The process is straightforward enough for small-scale community biodiesel facilities, requiring only basic chemical-engineering equipment. Wider adoption would divert waste cooking oil from sewers and landfills while generating a renewable, low-carbon transport fuel. Future work should evaluate WCO with higher FFA content (> 5%) using a two-step acid-base process, and should collect engine dynamometer data to verify that WCO-FAME matches virgin biodiesel in performance and emissions over extended operation.

Acknowledgements**Funding Sources**

This work was supported by an Engineering and Physical Sciences Research Council Doctoral Training Partnership grant.

Institutional Support

The Oxbridge Institute of Science, Cambridge, and the Royal Westfield University, Manchester, provided reactor facilities and analytical instrumentation.

Contributions Not Qualifying for Authorship

Mr. James Hartley coordinated WCO collection from participating restaurants.

References

1. Toop G, Alberici S, Spoettle M, van Steen H. Trends in the UCO market. London: ECOFYS; 2014.
2. Pastore C, Lopez A, Lotito V, Mascolo G. Biodiesel from dewatered wastewater sludge. *Bioresour Technol*. 2013;128:136-143.
3. Leung DY, Wu X, Leung MKH. A review on biodiesel production using catalyzed transesterification. *Appl Energy*. 2010;87(4):1083-1095.
4. Knothe G, Steidley KR. Kinematic viscosity of biodiesel fuel components and related compounds. *Fuel*. 2005;84(9):1059-1065.
5. Math MC, Kumar SP, Chetty SV. Technologies for biodiesel production from used cooking oil—a review. *Energy Sustain Dev*. 2010;14(4):339-345.
6. Canakci M, Van Gerpen J. Biodiesel production from oils and fats with high free fatty acids. *Trans ASAE*. 2001;44(6):1429-1436.
7. Meng X, Chen G, Wang Y. Biodiesel production from waste cooking oil via alkali catalyst and its engine test. *Fuel Process Technol*. 2008;89(9):851-857.
8. Predojević ZJ. The production of biodiesel from waste frying oils: a comparison of different purification steps. *Fuel*. 2008;87(17-18):3522-3528.
9. Phan AN, Phan TM. Biodiesel production from waste cooking oils. *Fuel*. 2008;87(17-18):3490-3496.
10. Fairfax A, Ashworth A. Internal laboratory records. Oxbridge Institute of Science and Royal Westfield University; 2023.
11. Vicente G, Martínez M, Aracil J. Integrated biodiesel production: a comparison of different homogeneous catalyst systems. *Bioresour Technol*. 2004;92(3):297-305.
12. Freedman B, Pryde EH, Mounts TL. Variables affecting the yields of fatty esters from transesterified vegetable oils. *J Am Oil Chem Soc*. 1984;61(10):1638-1643.
13. Ma F, Hanna MA. Biodiesel production: a review. *Bioresour Technol*. 1999;70(1):1-15.
14. Encinar JM, González JF, Rodríguez-Reinares A. Biodiesel from used frying oil. Variables affecting the yields and characteristics of the biodiesel. *Ind Eng Chem Res*. 2005;44(15):5491-5499.
15. Zhang Y, Dubé MA, McLean DD, Kates M. Biodiesel production from waste cooking oil: 1. Process design and technological assessment. *Bioresour Technol*. 2003;89(1):1-16.
16. Meher LC, Vidya Sagar D, Naik SN. Technical aspects of biodiesel production by transesterification—a review. *Renew Sustain Energy Rev*. 2006;10(3):248-268.
17. Demirbas A. Biodiesel from waste cooking oil via base-catalytic and supercritical methanol transesterification. *Energy Convers Manag*. 2009;50(4):923-927.
18. Kulkarni MG, Dalai AK. Waste cooking oil—an economical source for biodiesel: a review. *Ind Eng Chem Res*. 2006;45(9):2901-2913.
19. Gui MM, Lee KT, Bhatia S. Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. *Energy*. 2008;33(11):1646-1653.
20. Lotero E, Liu Y, Lopez DE, Suwannakarn K, Bruce DA, Goodwin JG. Synthesis of biodiesel via acid catalysis. *Ind Eng Chem Res*. 2005;44(14):5353-5363.