CHEMICAL ENGINEERING TRANSACTIONS
VOL. 94, 2022

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors:Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, Sandro Nižetić

ISBN978-88-95608-93-8;**ISSN** 2283-9216
DOI: 10.3303/CET2294183

A Review of Performance and Emission Characteristic of Engine Diesel Fuelled by Biodiesel

Lai Fatt Chuah[a,*], Awais Bokhari[b], Saira Asif[c], Jiří Jaromír Klemeš[d], Daniel Joe Dailin[e,f], Hesham El Enshasy[e,f,g], Abdul Halim Mohd Yusof[f]

[a]Faculty of Maritime Studies, Universiti Malaysia Terengganu, 21300 Kuala Terengganu, Terengganu, Malaysia.
[b]Department of Chemical Engineering, COMSATS University Islamabad, Lahore Campus, 54000 Pakistan
[c]Faculty of Sciences, Department of Botany, PMAS Arid Agriculture University, Murree Road, Rawalpindi, Punjab, 46300 Pakistan.
[d]Sustainable Process Integration Laboratory, SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology, VUT Brno, Technická 2896/2, 616 69, Brno, Czech Republic
[e]Institute of Bioproduct Development, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia.
[f]School of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310, Skudai, Johor, Malaysia.
[g]Bioprocess Development Department, City for Scientific Research and Technology Applications (SRTA), New Burg Al Arab, Alexandria, Egypt
lfchuah@umt.edu.my

Research into biodiesel as a greener fuel alternative derived from renewable resources has been increased due to the depletion of fossil-fuel reserves, as well as growing environmental concerns. It is a cleaner alternative fuel that may be utilised in diesel engines without requiring any modifications to the engine. This document provides a synopsis of key research on the engine performance and exhaust emission characteristics of diesel engines that are fuelled with biodiesel blends, as well as the results of those investigations. Based on the engine performance tests, biodiesel blends exhibited greater brake specific fuel consumption and exhaust gas temperature than diesel fuel, but poorer braking power, torque, and thermal efficiency. When comparing engine emissions from biodiesel blends to diesel fuel, it was found that carbon dioxide and nitrogen oxides were greater, but that carbon monoxide was surprisingly lower. The most significant advantage of biodiesel is that it is carbon neutral and does not contribute to the emission of greenhouse gases. It contributes to a reduction in pollution by minimising the release of dangerous and hazardous compounds into the atmosphere, as well as significantly improving the performance of the engine.

1. Introduction

A multitude of industries, including transportation (Chuah et al., 2021a) and construction, use diesel engines as prime movers because of their great thermal efficiency. Diesel fuel consumption has skyrocketed as a result of this. Diesel engines' high emissions of nitrogen oxides and particulate matter raise serious issues (Chuah et al., 2016a). Reducing nitrogen oxides and particulate matter in a conventional diesel engine is a challenging task. It is crucial to improve the fuel efficiency and towards lower carbon dioxide emissions by minimising nitrogen oxides and particles in diesel exhaust. The researchers looked at a variety of alternative fuels (Asif et al., 2021), including alcohol and its derivatives, dimethyl ether, and biodiesel fuels (transesterified from non-edible oils) (Chuah et al., 2015), among others. Non-edible oil is a sustainable energy source (Chuah et al., 2017), biodegradable (Ali et al., 2019), and non-toxic (Bokhari et al., 2015) alternative to petroleum-based diesel fuel. Among the several alternative fuels, biodiesel is one of the most well-suited for use in diesel engines (Chuah et al., 2021b).
Biodiesel made from edible oils accounts for about 95 % of global production. As a result of a food dispute, it has been aggressively criticised by non-governmental organisations around the world (Bokhari et al., 2016). Biodiesel's primary cost driver is the price of raw materials, accounting for 75 to 88 % of the total (Bokhari et al., 2017). By utilising the non-edible oil as a raw material in biodiesel production can significantly reduce total

Paper Received: 14 May 2022; Revised: 01 June 2022; Accepted: 03 June 2022
Please cite this article as: Chuah L.F., Bokhari A., Asif S., Klemeš J.J., Dailin D.J., Enshasy H.E., Yusof A.H.M., 2022, A Review of Performance and Emission Characteristic of Engine Diesel Fuelled by Biodiesel, Chemical Engineering Transactions, 94, 1099-1104 DOI:10.3303/CET2294183

biodiesel processing cost (Asif et al., 2019). The number of publications related to biodiesel, its diesel engine emissions and performances increased exponentially in the last 20 years, which revealed the increasing interest of the biodiesel and its environmental concern (Bokhari et al., 2019). Poor storage and cold flow properties, poor spray characteristics, and a lower heat content are only a few of the downsides of biodiesel fuel. Chuah et al. (2016b) stated that selection of the raw material oils is dependent on the critical parameters of the biodiesel, such as cetane number (≥ 51), iodine value (≤ 120 g I_2/100 g), cold filter plugging point (-10 – 0 ˚C) and oxidation stability (≥ 6h). By properly selecting the raw materials for biodiesel production, could possible to avoid these drawbacks altogether. It has also been observed that the use of biodiesel causes an increase in nitrogen oxide emissions. The presence of fuel bound oxygen leads to many implications for the increase in nitrogen oxides emission, including injection advancement, higher flame temperature, fuel property alterations in terms of increased density, lower volatility, higher iodine number, and a quicker burn rate. Because of the absence of sulphur and aromatics, as well as the presence of fuel-bound oxygen, biodiesel fuels have been demonstrated to lower soot emissions from internal combustion engines. Biodiesel fuels must be thoroughly investigated in order to be used as a substitute fuel for diesel engines. Its performance, combustion, and emission properties must all be investigated. As a result, the authors put up a concerted effort in this study to comprehensively analyse experimental research on biodiesel fuels from a variety of sources. To keep things short and simple, this research provides a fuel-vice summary of the performance and emission characteristics of biodiesel fuel.

2. Performance and emission characteristic of engine diesel

Several different types of diesel engines were examined by the researchers, with the majority of the engines being direct injection (DI) turbocharged and four-cylinder diesel engines. The performances and emissions of diesel engine fuelled biodiesel-diesel are influenced by biodiesel properties, e.g. viscosity, density, cetane number, calorific value, oxygen and sulphur content. High viscosity of biodiesel significantly affects the performance of the engine in terms of fuel spray, evaporation and atomisation process, which attributed to slow burning and longer combustion duration. When testing an engine on a test bench, equivalent performance requires attaining same engine speed and torque, regardless the fuel used. A meaningful comparison of emissions and fuel consumption is only possible if the test is carried out under the same operation mode, e.g. engine speed and brake mean effective pressure, the latter being proportional to the effective torque. Driver declared not noticing any power loss and it may be due to the infrequent demand of full load, in which low load is usually observed in a vehicle except when in highway express road (Lapuerta et al., 2008).

Pure biodiesel almost does not emit sulphur oxide during the combustion in a diesel engine as sulphur content can be ignored (Alpekin and Canakci, 2008). Sanjid et al. (2013) have reviewed papers of diesel engine performance fuelled by biodiesel derived from different feedstock oil compared to diesel fuel. They found that most researchers claimed brake specific fuel consumption and exhaust gas temperature increased, whereas the brake thermal efficiency, torque and brake power decreased when using biodiesel compared to diesel fuel during combustion in a diesel engine.

Kalam et al. (2011) carried out 5 wt.% blend of waste palm oil and waste coconut oil in four-cylinders naturally aspirated indirect injection (IDI) engine. Diesel fuel (B0) was used for comparison purposes. The engine operated from 1500-3500 rpm at a constant 85 % of throttle position. The engine operation showed good stability and safe at 85 % rather than 100 % throttle position. The brake power reached a maximum at 3000 rpm for all the tested fuel, e.g. 36.7, 36.1 and 36.2 kW for diesel fuel, 5 wt.% waste palm oil (P5) and 5 wt.% waste coconut oil (C5) blends. An average of engine power with all test biodiesel blends was lower than diesel fuel over the entire engine speed range at full load and was found as 28.28 kW (B0), 27.94 kW (P5) and 28.08 kW (C5). In comparison with diesel fuel, about 1.2 and 0.7 % reduction of brake power were found for P5 and C5. Moreover, reduction of exhaust emissions, e.g. unburned hydrocarbon, smoke and carbon monoxide offered by the blended fuels. In terms of nitrogen oxides, C5 reduced by 1 % and the P5 increased by 2 % compared to diesel fuel. Many studies have investigated the impact of biodiesel on nitrogen oxides emissions, and according to Xue et al. (2011), around 65 % of 69 number of references claimed that nitrogen oxides emissions rose as the biodiesel mix ratio increased.

For the experiments, the researchers (An et al., 2013) used a Euro IV diesel engine (in-line four cylinder, four stroke, turbocharged and direct injection diesel engine) to evaluate the performance, combustion, and emission characteristics of pure biodiesel derived from waste cooking oil as well as its blended fuels. Four different engine speeds of 800 - 3600 rpm under different loads of 25-100 % were tested. Using biodiesel mix fuels resulted in greater brake specific fuel consumption, particularly at low engine speeds and under partial load situations The brake thermal efficiency of biodiesel blend fuels was found to be slightly higher compared to diesel fuel at 50 and 100 % load and the opposite trend was found at 25 % load. When comparing the combustion characteristics of biodiesel and diesel fuel when the engine is working at full load, it was discovered that biodiesel had a slightly shorter ignition delay and a lower peak heat release rate. When it comes to exhaust emissions, the usage of biodiesel was shown to result in a modest reduction in significant pollutants, such as unburned hydrocarbons and nitrogen oxides. The opposite tendency was seen at low engine speed, indicating that low engine speed has a substantial impact on the combustion and emission production processes within the engine. Utlu and Kocak (2008) have carried out an experiment on a TDI 110 Turbo-Inter Cooler with In-line four cylinder, turbocharged and direct injection diesel engine to evaluate the emission and performance characteristics of pure biodiesel and diesel fuel under full load at various engine speeds of 1750 to 4400 rpm. The results showed that the waste frying oil methyl ester resulted in higher brake specific fuel consumption with 14.34 % increase in average compared to diesel fuel due to a lower heating value, higher density and viscosity of waste frying oil methyl ester. With respect to emissions, an average value of carbon monoxide, nitrogen oxides and smoke intensity was decreased by 17.14, 1.45 and 22.46 % for the utilisation of waste frying oil methyl ester compared to diesel fuel.

Nantha Gopal et al. (2014) have conducted the experiments on a single cylinder 4 stroke and vertical air-cooled DI diesel engine designed for agriculture purpose to evaluate the performance, combustion and emission characteristic of pure biodiesel derived from waste cooking oil and its blend fuels. An engine was run at 1500 rpm and the load was varied from no load to maximum load in 5 steps. The brake thermal efficiency, carbon monoxide, unburned hydrocarbon and smoke opacity were found to be lower in the case of biodiesel blend fuels compared to diesel fuel. Specific fuel consumption and nitrogen oxides of biodiesel blends fuel were observed to be higher than diesel fuel. For combustion characteristics, all biodiesel blends showed similar trends compared to diesel fuel. Ghobadian et al. (2009) studied artificial neural network (ANN) modelling of a diesel engine fuelled by the biodiesel blend fuels to predict the brake power, torque, specific fuel consumption and exhaust emissions of the engine. To acquire data for training and testing the proposed artificial neural network, they have conducted the experiments on a RD270 Ruggerini diesel engine of two cylinders and four strokes to evaluate the performance and emission characteristic of pure biodiesel derived from waste vegetable oil and its blend fuels ranging from B0 to B50. Seven different engine speeds of 1200, 1600, 2000, 2400, 2800, 3200 and 3600 rpm at 100 % load were studied. The results showed that the artificial neural network model can predict the engine performance and exhaust emissions well with a correlation coefficient (R^2) of 0.9487 (torque), 0.999 (specific fuel consumption), 0.929 (carbon monoxide) and 0.999 (hydrocarbon). The torque, brake thermal efficiency, carbon monoxide and unburned hydrocarbon were found to be lower in the case of biodiesel blend fuels compared to diesel fuel. Specific fuel consumption of biodiesel blends fuel was observed to be higher than diesel fuel.

Ong et al. (2014) have conducted the experiments on a TF120M Yanmar diesel engine of single cylinder, four strokes and direct injection diesel engine to evaluate the engine performance and emission characteristic using Jatropha curcas (JC), Ceiba pentandra (CP) and Calophyllum inophyllum (CI) biodiesel and its blended fuels (B10-B50). The engine was tested at 100 % throttle opened wide at various speeds from 1500 to 2400 rpm with an interval of 100 rpm. The torque, brake power, carbon dioxide and smoke opacity were found to be lower in the case of all different sources of biodiesel blend fuels compared to diesel fuel. On the other hand, specific fuel consumption, exhaust gas temperature, unburned hydrocarbon, carbon monoxide and nitrogen oxides were observed to be higher using biodiesel blends fuel compared to diesel fuel. From the view point of the engine performance, B10 was the best blending ratio among the others.

Superior physicochemical properties of mustard biodiesel (MB) derived from waste mustard oil have been investigated by Ahmed et al. (2014) using an Inline four-cylinder Mitsubishi Pajero diesel engine to evaluate emission and performance characteristics compared to diesel fuel. The engine was operated between 1000 and 4000 rpm at 500 rpm intervals under 100 % load condition. For engine performance test, 10 and 20 wt.% mustard biodiesel blends showed 8-13 % higher mean brake specific fuel consumption and 7-8 % less mean brake power compared to diesel fuel. Engine emissions characteristics showed 9-12 % higher means nitrogen oxides, 24-42 % lower mean hydrocarbon and 19-40 % lower carbon monoxide compared to diesel fuel. They concluded that the both MB10 and MB20 without antioxidants addition can be used in diesel engines without any modifications.

Liaquat et al. (2013) have conducted the experiments on a single cylinder diesel engine of four strokes and direct injection diesel engine to evaluate the engine performance and emission characteristic using coconut biodiesel (CB) and its blend (CB5 and CB15). The engine was tested at 100 % throttle wide opened at various speeds from 1500 to 2400 rpm with an interval of 100 rpm. The engine performance experiments indicated that CB blend fuels caused a slight increase in brake specific fuel consumption values, while a slight decrease in torque and brake power values over the entire range compared to diesel fuel. Exhaust emission tests revealed that hydrocarbon and carbon monoxide emission values decreased, while nitrogen oxides and carbon dioxide emission values increased with coconut biodiesel usage compared to diesel fuel. Both CB5 and CB15 can be utilised in diesel engines without the need for any engine changes.

Table1: Overview on diesel engine performance and emissions from different feedstock and diesel fuel

Author	Source	Fuel properties	Engine make, model and type	Torque (Nm)	BP (kW)	BET (%)	BSFC (g/kWh)	BSEC (MJ/kWh)	EGT (°C)	HC (ppm)	CO (vol.%)	CO_2 (vol.%)	NOx (ppm)
Liaquat et al., 2013	Diesel	CN-51, HV-46 MJ/kg	4 stroke DI diesel engine	22.2	5.1	-	282	-	270	18	0.8	3.34	400
	Coconut oil -B5	CN-52, HV-45 MJ/kg		22	5	-	287	-	278	16	0.7	3.4	410
	Coconut oil -B15	CN-53, HV44 MJ/kg		21.6	4.9	-	290	-	280	14	0.64	3.46	420
Rizwanul Fattah et al., 2014	Diesel	OS-59h, HV-45 MJ/kg	4 cylinder, 4 stroke, indirect injection diesel engine	-	35.1	-	385	17	-	19	0.65	-	203
	CIME-B20	OS-73h, HV-44 MJ/kg		-	34.6	-	405	17.5	-	15	0.45	-	212
	CIME-B20 + BHA	OS-96h, HV-44 MJ/kg		-	34.7	-	400	17.3	-	16	0.52	-	203
	CIME-B20 + BHT	OS-94h, HV-44 MJ/kg		-	34.7	-	395	17.2	-	17	0.54	-	210
	CIME-B20 + TBHQ	OS-93h, HV-44 MJ/kg		-	34.8	-	393	17.1	-	18	0.55	-	206
Nantha Gopal et al., 2014	Diesel	HV-45 MJ/kg	One cylinder, Four stroke, vertical air cooled diesel engine	-	-	29	280	12.5	-	38	0.42	-	600
	WCOME- B20	HV-43 MJ/kg		-	-	28	320	13	-	22	0.17	-	620
	WCOME - B40	HV-42 MJ/kg		-	-	27	340	13.5	-	21	0.26	-	640
	WCOME - B80	HV-40 MJ/kg		-	-	26	350	14	-	18	0.27	-	670
	WCOME	HV-39 MJ/kg		-	-	25	380	15	-	16	0.29	-	710
An et al., 2013	Diesel	CN-52, HV-45 MJ/kg	Euro IV, in-line four cylinder, turbocharged, DI	-	50	39.3	225	-	-	8	50 ppm	8.9	850
	WCOME-B10	CN-53, HV-43 MJ/kg		-	49	36.5	-	-	-	-	100 ppm	8.8	840
	WCOME-B50	CN-55, HV-41 MJ/kg		-	47	38.1	-	-	-	-	105 ppm	8.4	835
	WCOME	CN-58, HV-38 MJ/kg		-	44	33.0	250	-	-	6	110 ppm	7	790
Utlu and Kocak, 2008	Diesel	CN-49, HV-43 MJ/kg	TDI 110 Turbo-inter Cooler, four cylinder, direct injection	220	72.4	-	229.59	-	539	-	876 ppm	10.6	482
	WCOME	CN-52, HV-39 MJ/kg		216.8	72	-	258.66	-	499	-	665 ppm	10.2	465

Note: Method process = Mechanical stirring; B = Percentage of biodiesel mixed with percentage of diesel; ME = methyl ester, CI = *C. inophyllum*, WCO = waste cooking oil

3. Conclusions

Biodiesel blends demonstrated a lower level of brake thermal efficiency (1.0–13.8 %). According to the findings of the tests, the braking power of biodiesel blends is likewise a little bit lower than that of pure diesel (0.9–12.5 % less than diesel fuel). According to the trend, the proportion of biodiesel used in the blends has an effect on the amount of braking power that is produced. In the same vein, this also holds true for the torque. When increasing the proportion of biodiesel in the fuel blend (0.6-8.1 %), the torque values see a decrease due to its lower calorific value, biodiesel and its blends increase fuel consumption and decrease brake power and torque. The majority of the authors reported that the increase of brake specific fuel consumption while using biodiesel may be attributed by higher density, viscosity, and calorific value of the biodiesel compared to pure diesel (1.8–35.7 %). Even though biodiesel and its blends have a lower heating value compared to diesel fuel, they have a net heat release rate that is slightly lower, as well as lower thermal efficiency and higher brake specific fuel consumption. In diesel engines, utilising biodiesel as a fuel has been shown to significantly reduce hydrocarbon emissions (by 10.5-77.4 %) and carbon monoxide emissions (by 2.0-59.5 %). Because of its higher cetane number and enriched oxygen content, biodiesel produces less carbon monoxide, hydrocarbon, and particulate matter than diesel. A large number of scientists have arrived at the conclusion that the higher oxygen contents of biodiesel are to blame for the increases in carbon dioxide (1.1–21.3 %) and nitrogen oxide (4.5–20.5 %) that occur as a result of utilising biodiesel. The increased oxygen contents will contribute to the completion of the combustion process, which will result in a higher temperature for the combustion process. Despite the fact that biodiesel produces more carbon dioxide, it is regarded as carbon-neutral. Biodiesel does not contain any sulphur and aromatic compounds and hence does not emit any sulphurous components. Because of the varied tested engines, operating circumstances or driving cycles, kind of biodiesel, measuring procedures or equipment, and other factors, there have always been inconsistencies in the performance and emissions of biodiesel engines. In addition to this, the earlier injection timing that was achieved by the engine when it was fuelled with biodiesel contributed to a reduction in the overall amount of hydrocarbon emissions. This convergence of tendencies is beginning to take shape. It is possible to utilise biodiesel blends of up to 20 % as an alternative fuel in diesel engines with little or no modification. Developing the optimum biodiesel blend, the optimum blend ratio (up to 50 %), and the most cost-effective green additive is the focus of further research. It is not now economically possible to use biodiesel. For biodiesel to be competitive with other traditional sources of energy, improved technological advancements and supportive legislation are required. More study on long-term difficulties such as engine deposits, injector choking, and contamination of the engine is required in order to enhance the performance of a biodiesel-powered diesel engine.

Acknowledgements

The authors would like to acknowledge the support from the project “Sustainable Process Integration Laboratory – SPIL” funded by EU CZ Operational Programme Research and Development, Education, Priority1: Strengthening capacity for quality research (Grant No. CZ.02.1.01/0.0/0.0/15_003/000045). The authors gratefully acknowledge the Ministry of Higher Education (MOHE), Universiti Malaysia Terengganu (UMT) and Universiti Utara Malaysia (UUM). Heartfelt appreciation to the Chief Engineer Kevin Chin Ket Vui, Chief Mate Lim Poh Keong, Jenna Tan Ying Min, Dr. Loy Kak Choon, Tan Lee Chwin, Chew Kuan Lian, Teh Bee Bee, Loh Chong Hooi, Timmy Chuah Tim Mie and Ong Shying Weei for their support. The authors would also like to thank Research Management Center at Universiti Teknologi Malaysia (UTM), Malaysia for the support through grant No. Q.J130000.3651.03M30.

References

Ahmed S., Hassan M. H., Kalam M. A., Ashrafur Rahman S. M., Abedin M. J., Shahir A., 2014, An experimental investigation of biodiesel production, characterization, engine performance, emission and noise of Brassica juncea methyl ester and its blends, Journal of Cleaner Production, 79, 74-81.

Ali B., Yusup S., Quitain A.T., Bokhari A., Kida T., Chuah L.F., 2019, Heterogeneous catalytic conversion of rapeseed oil to methyl esters: optimization and kinetic study In: M Hosseini (Ed.), Advances in feedstock conversion technologies for alternative fuels and bioproducts. New Technologies, Challenges and Opportunities Woodhead Publishing Series in Energy, 221-238.

Alptekin E., Canakci M., 2008, Determination of the density and the viscosities of biodiesel–diesel fuel blends, 2008, Renewable Energy, 33, 2623-2630.

An H., Yang W. M., Maghbouli A., Li J., Chou S. K., Chua K. J., 2013, Performance, combustion and emission characteristics of biodiesel derived from waste cooking oils, Applied Energy, 112, 493-499.

Asif S., Ahmad M., Bokhari A, Chuah L.F., Zafar M., Sultana S., Mir S., 2019, Chemical conversion in biodiesel refinery In: A Rastegari, A Yadav, A Gupta (Eds), Prospects of renewable bioprocessing in future energy systems. Biofuel and Biorefinery Technologies, Vol 10, Springer, Cham, 201-217.

Asif S., Klemes J.J., Mukhtar A., Saqib S., Chuah L.F., Bokhari A., 2021, Intensification of biodiesel synthesis in a cavitation system from Xanthium Spinosum oil, Chemical Engineering Transactions, 86, 151-156.

Bokhari A., Chuah L.F., Yusup S., Ahamd J., Shamsuddin, M.R., Teng M.K., 2015, Microwave-assisted methyl esters synthesis of Kapok (*Ceiba pentandra*) seed oil: parametric and optimisation study, Biofuel Research Journal, 7, 281-287.

Bokhari A., Chuah L.F., Yusup S., Klemeš J.J., Kamil R.N.M., 2016, Optimisation on pretreatment of rubber seed (*Hevea brasiliensis*) oil via esterification reaction in a hydrodynamic cavitation reactor, Bioresource Technology, 199, 414-422.

Bokhari A., Yusup S., Chuah L.F., Klemeš J.J., Asif S., Ali B., Akbar M.M., Kamil R.N.M., 2017, Pilot scale intensification of rubber seed (*Hevea brasiliensis*) oil via chemical interesterification using hydrodynamic cavitation technology, Bioresourse Technology, 242, 272-282.

Bokhari A, Chuah L.F., Michelle L.Z.Y., Asif S., Shahbaz M., Akbar M.M., Inayat A., Jamil F., Naqvi S.R., Yusup S., 2019, Mirowave enhanced catalytic conversion of canola-based methyl ester: optimization and parametric study In: AK Azad, M Rasul (Eds), Advanced biofuels: applications, technologies and environmental sustainability, Woodhead Publishing Series in Energy, 153-166.

Bokhari A., Yusup S., Asif S., Chuah L.F., Michelle L.Z.Y., 2020, Process intensification for the production of canola-based methyl ester via ultrasonic batch reactor: optimization and kinetic study In: L Singh, A Yousuf, DM Mahapatra (Eds), Bioreactors sustainable design and industrial applications in mitigation of GHG emissions, Elsevier Inc, 27-42.

Chuah L.F., Yusup S., Abd Aziz A.R., Bokhari A., 2015, Performance of refined and waste cooking oils derived from palm olein on synthesis methyl ester via mechanical stirring, Australian Journal of Basic and Applied Sciences 9(37), 445-448.

Chuah L.F., Abd Aziz A.R., Yusup S., Klemeš J.J., Bokhari A., 2016a, Waste cooking oil biodiesel via hydrodynamic cavitation on a diesel engine performance and greenhouse gas footprint reduction, Chemical Engineering Transactions, 50, 301-306.

Chuah L.F., Yusup S., Abd Aziz A.R., Klemeš J.J., Bokhari A., Abdullah M.Z., 2016b, Influence of fatty acids content in non-edible oil for biodiesel properties, Journal of Clean Technologies and Environmental Policy 18(2), 473-482.

Chuah L.F., Klemeš J.J., Yusup S., Bokhari A., Akbar M.M., 2017, Influence of fatty acids in waste cooking oil for cleaner biodiesel, Journal of Clean Technologies and Environmental Policy, 3, 1-10.

Chuah L.F., Klemes J.J., Bokhari A., Asif S., 2021a, A review of biodiesel production from renewable resources: chemical reactions, Chemical Engineering Transactions, 88, 943-948.

Chuah L.F., Mohd Salleh N.H., Osnin N.A., Alcaide J.I., Abdul Majid M.H., Abdullah A.A., Bokhari A., Jalil E.E.A., Klemes J.J., 2021b, Profiling Malaysian ship registration and seafarers for streamlining future Malaysian shipping governance, Australian Journal of Maritime & Ocean Affairs, 1, 225-261.

Ghobadian B., Rahimi H., Nikbakht A. M., Najafi G., Yusaf T. F., 2009, Diesel engine performance and exhaust emission analysis using waste cooking biodiesel fuel with an artificial neural network, Renewable Energy, 34, 976-982.

Kalam M. A., Masjuki H. H., Jayed M. H., Liaquat A. M., 2011, Emission and performance characteristics of an indirect ignition diesel engine fuelled with waste cooking oil, Energy, 36, 397-402.

Lapuerta M., Armas O., Rodríguez-Fernández J., 2008, Effect of biodiesel fuels on diesel engine emissions, Progress in Energy and Combustion Science, 34, 198-223.

Liaquat A. M., Masjuki H. H., Kalam M. A., Rizwanul Fattah I. M., Hazrat M. A., Varman M., 2013, Effect of coconut biodiesel blended fuels on engine performance and emission characteristics, Procedia Engineering, 56, 583-590.

Nantha Gopal K., Pal A., Sharma S., Samanchi C., Sathyanarayanan K., Elango T., 2014, Investigation of emissions and combustion characteristics of a CI engine fueled with waste cooking oil methyl ester and diesel blends, Alexandria Engineering Journal, 53, 281-287.

Ong H. C., Masjuki H. H., Mahlia T. M. I., Silitonga A. S., Chong W. T., Yusaf T., 2014, Engine performance and emissions using *Jatropha curcas*, *Ceiba pentandra* and *Calophyllum inophyllum* biodiesel in a CI diesel engine, Energy, 69, 427-445.

Rizwanul Fattah I. M., Hassan M. H., Kalam M. A., Atabani A. E., Abedin M. J., 2014, Synthetic phenolic antioxidants to biodiesel: path toward NOx reduction of an unmodified indirect injection diesel engine, Journal of Cleaner Production, 79, 82-90.

Sanjid A., Masjuki H. H., Kalam M. A., Rahman S. M. A., Abedin M. J., Palash S. M., 2013, Impact of palm, mustard, waste cooking oil and *Calophyllum inophyllum* biofuels on performance and emission of CI engine, Renewable and Sustainable Energy Reviews, 27, 664-682.

Utlu Z., Koçak M. S., 2008,The effect of biodiesel fuel obtained from waste frying oil on direct injection diesel engine performance and exhaust emissions, Renewable Energy, 33, 1936-1941.

Xue J., Grift T. E., Hansen A. C., 2011, Effect of biodiesel on engine performances and emissions, Renewable and Sustainable Energy Reviews, 15, 1098-1116.