

SIMULATION OF PERFORMANCE AND OPTIMIZATION FOR DIESEL
ENGINE FUELED WITH HIGHER BIODIESEL BLEND

YOSUA SETIAWAN

UNIVERSITI TEKNOLOGI MALAYSIA

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YOSUA SETIAWAN

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ABSTRACT

With global energy demand that keeps on increasing by 1.2% every year, CO₂ was predicted to increase as well. A short-term solution to reduce CO₂ is to switch to carbon-neutral fuels and one of them is biodiesel. However, biodiesel's higher viscosity and lower calorific value compared to pure petroleum diesel lead to higher brake specific fuel consumption (BSFC) especially for higher biodiesel blend. Even though there are many ways to reduce the BSFC, to quantify how much these ways manage to reduce it requires experiments that are costly and time consuming. At the same time, a limited simulation model can be used as the alternative to the experiments. Therefore, the objective of this research is to develop a model based on the Yanmar L70N6 engine using GT-Suite simulation software, to predict engine performance, combustion, and emissions when using biodiesel. The engine model was then used to simulate a high biodiesel blend with a variation of injection timing (IT), injection pressure (IP), and preheat biodiesel fuel (PF). In this research, experimental work was conducted to obtain baseline data for validating the simulation study based on the manufacturer's default setting of IP (206 bar), IT (14 °bTDC), and ambient temperature for fuel which is around 30°C. In the experiment, B10 and B30 were tested at four different speeds (1500, 2000, 2500, and 3000 rpm) with five different loads (3, 5, 7.5, 10, and 11.5 Nm) at each speed. Then, B30, B50, B70, and B100 were simulated with variations of IP (206, 220, 240, 260, 280, and 300 bars), IT (10, 12, 14, 16, 18, 20, 22, and 24 °bTDC) and PF (30, 40, 50, 60, 70, 80, and 100°C). For model validation, the engine speed was simulated at 2000 rpm with five different loads and comparison between the simulation and the experimental results showed less than 10% differences in the BSFC of B10 (8.8%) and B30 (5.1%). The results showed that by increasing IP to 300 bar, retarding IT to 12°bTDC, and PF to 100°C, reduction of the BSFC was recorded from 2.1% to 5.4% meanwhile CO₂ emission reduction was recorded from 3.79% to 10.7% and by combining three optimized parameters, it helps reducing BSFC, and CO₂ for all blends. Among all biofuels, B100 has the lowest BSFC (8.8%) and CO₂ (22.3%) at 3000 rpm and 3 Nm load. In conclusion, the objective of the research, which is to develop a reliable simulation model and improve the performance of a high biodiesel blend, has been achieved successfully.

ABSTRAK

Dengan permintaan tenaga global yang terus meningkat sebanyak 1.2% setiap tahun, CO₂ diramalkan akan meningkat juga. Untuk mengurangkan CO₂ dalam masa terdekat adalah dengan beralih kepada bahan api neutral karbon dan salah satunya ialah biodiesel. Kelikatan biodiesel yang lebih tinggi dan nilai kalori yang lebih rendah berbanding diesel petroleum membawa kepada penggunaan bahan api khusus brek (BSFC) yang lebih tinggi. Meskipun terdapat banyak cara untuk mengurangkan BSFC, tetapi ianya memerlukan pengujian yang mahal dan memakan masa. Sementara itu, model simulasi yang boleh digunakan sebagai alternatif kepada eksperimen juga adalah terhad. Oleh itu, objektif penyelidikan ini adalah untuk membangunkan model berasaskan enjin Yanmar L70N6 menggunakan perisian simulasi GT-Suite, untuk meramal prestasi enjin, pembakaran, dan pelepasan. Model tersebut kemudiannya digunakan untuk mensimulasikan biodiesel dengan variasi pemasaan suntikan (IT), tekanan suntikan (IP) dan bahan api biodiesel prapanas (PF). Dalam penyelidikan ini, kerja eksperimen dijalankan berdasarkan penetapan lalai pengeluar IP (206 bar), IT (14 °bTDC), dan suhu ambien untuk bahan api iaitu sekitar 30°C. Dalam eksperimen, B10 dan B30 diuji pada empat kelajuan berbeza (1500, 2000, 2500 dan 3000 rpm) dengan lima beban berbeza (3, 5, 7.5, 10, dan 11.5 Nm) pada setiap kelajuan. Kemudian, B30, B50, B70 dan B100 disimulasikan dengan variasi IP (206, 220, 240, 260, 280 dan 300 bar), IT (10, 12, 14, 16, 18, 20, 22 dan 24 °bTDC) dan PF (30, 40, 50, 60, 70, 80 dan 100°C). Untuk pengesahan model, kelajuan enjin disimulasikan pada 2000 rpm dengan lima beban berbeza dan perbandingan antara simulasi dan keputusan eksperimen menunjukkan perbezaan kurang daripada 10% dalam BSFC B10 (8.8%) dan B30 (5.1%). Dengan meningkatkan IP kepada 300 bar, melambatkan IT kepada 12°bTDC, dan PF kepada 100°C, pengurangan BSFC direkodkan daripada 2.1% kepada 5.4% dan pengurangan pelepasan CO₂ direkodkan daripada 3.79% kepada 10.7 % dan ianya juga membantu mengurangkan BSFC, dan CO₂ untuk semua bahan api. Di antara semua biofuel, B100 mempunyai BSFC (8.8%) dan CO₂ (22.3%) paling rendah pada 3000 rpm dan beban 3 Nm. Kesimpulannya, objektif penyelidikan, iaitu untuk membangunkan model simulasi yang boleh dipercayai dan meningkatkan prestasi biodiesel yang berbeza, telah dicapai dengan jayanya.

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LIST OF ABBREVIATIONS

ASTM	-	American Society for Testing and Materials
B0	-	Biodiesel (0%)
B05	-	Biodiesel (5%)
B10	-	Biodiesel (10%)
B100	-	Biodiesel (100%)
B20	-	Biodiesel (20%)
B25	-	Biodiesel (25%)
B30	-	Biodiesel (30%)
B40	-	Biodiesel (40%)
B50	-	Biodiesel (50%)
B60	-	Biodiesel (60%)
B70	-	Biodiesel (70%)
BEV	-	Battery Electric Vehicle
BMEP	-	Brake Mean Effective Pressure
BP	-	Brake Power
BSFC	-	Brake Specific Fuel Consumption
BTE	-	Brake Thermal Efficiency
CA	-	Crank Angle
CI	-	Compression Ignition
CO	-	Carbon Monoxide
CO ₂	-	Carbon Dioxide
CRDI	-	Common Rail Direct Injection
DI	-	Direct Injection
ECU	-	Electronic Control Unit
EGR	-	Exhaust Gas Recirculator
EOI	-	End of Injection
EOS	-	Equation of State
EV	-	Electric Vehicle
FE	-	Finite Element
GHG	-	Green House Gases
H ₂	-	Hydrogen
H ₂ O	-	Hydrogen Oxide
HC	-	Hydro Carbon
HP	-	Horse Power
ICE	-	Internal Combustion Engine
ISO	-	International Standard Operation
LCD	-	Liquid Crystal Display
MJ	-	Mega Joule
MPOB	-	Malaysia Palm Oil Board

MS	-	Malaysia Standard
N ₂	-	Nitrogen
NO _x	-	Nitrogen Oxides
O ₂	-	Oxygen
OH,	-	Hydroxide
POME	-	Palm Oil Methyl Ester
RPM	-	Revolution Per Minute
SI	-	Spark Ignition
SO	-	Sulphur Monoxide
SO ₂	-	Sulphur Dioxide
SOC	-	Start of Combustion
SOI	-	Start of Injection
TDC	-	Top Dead Centre
ULSD	-	Ultra Low Sulphur Diesel

LIST OF SYMBOLS

N	-	Revolution per Minute
T	-	Temperature
C_p	-	Carbon Produced
C_r	-	Carbon Reduction
\dot{m}_a	-	Mass Air Rate
C_D	-	Coefficient of Drag
D_o	-	Diameter of Orifice
ρ_a	-	Air Density
Δp	-	Pressure differentiation
ρ_{man}	-	Density of Manometer
g	-	Gravity Acceleration
h	-	Height/Head
V_d	-	Displacement Volume
\dot{m}_f	-	Mass Fuel Rate
η_{tb}	-	Thermal Efficiency
Q_{HV}	-	Heating Value

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CHAPTER 1

INTRODUCTION

1.1 Background Study

Global energy demand keep on increasing by 1.2% every year (Lešnik et al., 2020). Increase on global energy demand, means that it might cause increment in greenhouses gases (GHG) too. Research conduct by Lešnik et al. (2020), shown that in European countries around 33% of all the energy demand were used for transportation sector, and around 81.7% of it were used for road transport sector.

Therefore, many governments around the world are pushing their road transport sector especially in private transportation (i.e. cars) to be electrified (Shammut et al., 2019). Electrification of cars doesn't stop only in Hybrid or Plug-in Hybrid electric vehicle, but it will push to all electric vehicle, whether it will be battery electric vehicle (BEV) or hydrogen powered electric vehicle. For Example, Britain are planning to ban new car sales solely powered by Gasoline or Diesel in 2030 and Hybrid vehicle will be banned in 2038 onwards.

Study shown by Hu (2020) hydrogen might be another alternative than BEV, China already made plans for 2025 and 2030 for hydrogen fuel cell. The government of China sees hydrogen as future fuel. Even though hydrogen could be the future fuel, with the current price of manufacturing the fuel cell and hydrogen it self it can not compete with BEV. Hydrogen fuel cell needs to be cheaper and have a break through technologies to be able to compete against BEV and vehicle with internal combustion engine.

1.1.1 Challenge to Reduce Green House Gas

To achieve greenhouse gases reduction in developing or under developing countries, the ICE automobiles manufacturer needs to do something to reduce the greenhouse gases. There are two ways to reduce it, the first one is to improve the combustion efficiency and the second one is switching to carbon neutral fuel. Recent study shown by Ayompe et al. (2021) and Wahyono Y (2020) for countries like Indonesia and Malaysia, it will be easier to switch to carbon neutral fuel such as biodiesel. Both countries are the major palm oil production in the world (Ayompe et al., 2021). Study shown by Khalid et al. (2017) using palm oil as biodiesel feedstock, considered as one of the best biodiesel feed stock. Palm oil derivatives also considered as one of the best biodiesel feed stock, one of them is waste cooking oil (Priyadarshi & Paul, 2018). Based on the fact mentioned above, it is easier for both countries to switch to biodiesel. As shown on Figure 1.1, using biodiesel will reduce greenhouse gases.

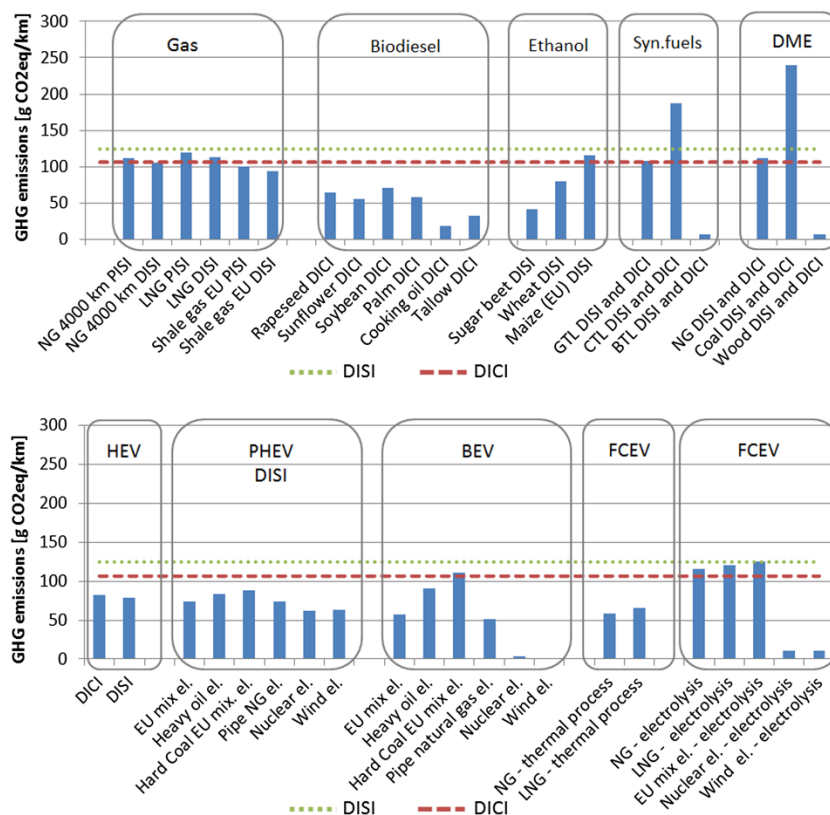


Figure 1.1. GHG emissions comparison (Lešnik et al., 2020).

1.1.2 Biodiesel Challenges

Using biodiesel to reduce greenhouse gases will be beneficial, because diesel engine is widely use in transportation sectors (Fridstrøm & Østli, 2021). Truck, bus and marine vehicle use diesel engine as their main propulsion. Therefore, usage of biodiesel as fuel will reduce greenhouse gases in transportation sector. Studies shown by C H et al. (2020), Abed et al. (2018) and Tziourtzioumis and Stamatelos (2017) shown clear benefits of using lower biodiesel blend as diesel engine fuel. There are clearly some reductions on greenhouse gases but, it might lead to reduce engine power output and tend to increase NO_x emission. Power decrease mainly caused by lower calorific value compared to petroleum diesel. To maximize greenhouse gas reduction in diesel engine, there are several things to do such as using high biodiesel blend fuel and optimized the overall engine performance to reduce power gap between petroleum diesel fuel and biodiesel fuel but still maintain reduction of overall emission.

Study shown by (Setiawan, 2019), using Mitsubishi 4D56 common-rail and biodiesel fuel between B0 to B50 using 100% load. It is clearly seen that higher biodiesel blend, tend to reduce power and torque output, especially on B50. Overall, B50 has the biggest power and torque reduction. B50 has 12.48% power reduction and 9.74% torque reduction.

1.2 Problem Statement

Diesel engine widely use in buses and trucks, recent study already shown several benefits of using biodiesel as diesel engine fuel, there are still some drawbacks of using biodiesel. In example, the power and torque from the engine might decrease as biodiesel blend get higher due to lower calorific value and even though biodiesel reduce CO, HC and CO₂, but NO_x emissions tend to be higher than petroleum diesel when it could be compared. In terms of heat release rate and ignition delay, biodiesel tend to have later ignition delay and lower heat release rate as shown by Azad et al. (2019). From brief literature review, some of the method of preheat fuel, variation of injection timing and injection pressure still use lower biodiesel blend in example they

usually use between B20 and B50. Even though it is known that higher biodiesel blend decreasing engine performance, certain country for example Indonesia are pushing to increase biodiesel percentage to B100. Therefore, it is necessary to develop this research with higher biodiesel blend and optimize the performance, combustion and emissions of each biodiesel blend using variation of injection timing, injection pressure and preheat biodiesel fuel using GT-Suite software.

1.3 Purpose Statement

The purpose of this study is to determine the effect of using high biodiesel blend on diesel engines and optimize it with variation of injection timing, injection pressure and preheat biodiesel fuel and perform 1-D modelling simulation with GT-Suite. Optimization is done to get the optimum power and torque but can reduce NO_x emissions as well.

1.4 Research Question

1. How to simulate single cylinder diesel engine performance, combustion and emissions using high biodiesel blend from Palm Oil Methyl Ester?
2. How to improve engine performance, combustion and emissions using high biodiesel blend from Palm Oil Methyl Ester?

1.5 Objectives

OBJ1. To develop a validated single cylinder diesel engine model for the prediction of engine performance, combustion, and emissions.

OBJ2. To improve engine performance, combustion and emissions of high biodiesel blend on diesel engine with variation of injection timing, injection pressure, preheat biodiesel fuel.

1.6 Scope

This research was conducted in a single cylinder diesel engine with B10 and B30 as baseline data. Then a model of a single cylinder diesel engine was developed in 1-D simulation software. The simulation was carried out in GT-Suite, GT-Suite was chosen because it has met international standards.

Simulation was conducted in GT-Suite using B10 and B30 as baseline data and validation for the model. Biodiesel that was used is B50, B70, and B100. These biodiesel blends were chosen because the blend will soon be used in Indonesia. Currently Indonesia is using B30 as the diesel fuel and Indonesian government are ready to implement B40 by 2023. It is also known that Indonesian government are pushing to use B100 in the next 5 years. Palm Oil Methyl Ester (POME) will be used in this research because palm oil is the main biodiesel feedstock in Malaysia and were provided by Malaysia Palm Oil Board. Biodiesel from MPOB has already met the MS 2008: 2008. In the future, palm oil might be substitute with waste cooking oil or other waste oil to avoid food fuel competition.

Performance parameters were brake thermal efficiency, brake specific fuel consumption, brake mean effective pressure, brake power, and brake torque. The combustion parameter was heat rate release. Meanwhile, emissions parameters were CO₂ and NO_x. To improve the engine performance, variation of injection timing, injection pressure, preheat biodiesel fuel were used to explore the engine potential. To validate the result of simulation, validation was done by reviewing other papers and journals.

1.7 Expected Project Outcome

This research is expected to overcome several issues of using higher biodiesel blend, especially for blend more than B50. Based on study by Churkunti et al. (2016), Said et al. (2018), Kaya and Kökkülünk (2020), and Lewiski et al. (2017) usage of high biodiesel blend in diesel engines leads to decrease power and torque output, but on the other sides CO₂, HC, and CO is decreasing. Therefore, it is needed to do optimization of diesel engines to have optimum power and torque output while still reducing the overall emissions. Result of this project could bring some idea on developing next generation of diesel engines and might reduce the cost of conducting engine research by doing simulation works.

1.8 Significant of Study

After this research was completed, it was expected to help eliminate diesel engine vehicle users who feel the vehicle is underpowered due to the higher biodiesel blend used for their vehicle so that the implementation of biodiesel can be applied more broadly.

This research does not require or require minimal changes to the components on the engine therefore, it could be easily implemented into the automotive industry. This study will not require any changes toward engine geometrical. One of the reasons is, generally, modern diesel vehicles already use ECUs in managing fuel injection to the combustion chamber. So, there is no need to modify engine components, by merely remapping the ECU it might increase the overall performance and emissions of the vehicle.

With the end of this research, it is also hoped that the use of biofuels as a renewable energy, specifically in Malaysia and Indonesia can be further developed, especially in land transportation and in maritime which use diesel engine.

REFERENCES

- Agarwal, A. K., Dhar, A., Gupta, J. G., Kim, W. I., Choi, K., Lee, C. S., & Park, S. (2015, 2015/02/01/). Effect of fuel injection pressure and injection timing of Karanja biodiesel blends on fuel spray, engine performance, emissions and combustion characteristics. *Energy Conversion and Management*, 91, 302-314. <https://doi.org/https://doi.org/10.1016/j.enconman.2014.12.004>
- Ahmadipour, S., Aghkhani, M. H., & Zareei, J. (2020). Investigation of injection timing and different fuels on diesel engine performance and emissions [Article]. *Journal of Computational and Applied Research in Mechanical Engineering*, 9(2), 385-396. <https://doi.org/10.22061/jcarme.2019.4143.1497>
- Ayompe, L. M., Schaafsma, M., & Egoh, B. N. (2021). Towards sustainable palm oil production: The positive and negative impacts on ecosystem services and human wellbeing [Review]. *Journal of Cleaner Production*, 278, Article 123914. <https://doi.org/10.1016/j.jclepro.2020.123914>
- Azad, A. K., Rasul, M. G., & Bhatt, C. (2019, 2019/01/01/). Combustion and emission analysis of Jojoba biodiesel to assess its suitability as an alternative to diesel fuel. *Energy Procedia*, 156, 159-165. <https://doi.org/https://doi.org/10.1016/j.egypro.2018.11.121>
- Churkunti, P., Mattson, J. M. S., & Depcik, C. (2016). Influence of Fuel Injection Pressure and Biodiesel upon NO_x Emissions <https://doi.org/10.4271/2016-01-0877>
- Clenci, A., Niculescu, R., Danlos, A., Iorga-Siman, V., & trica, a. (2016, 04/18). Impact of Biodiesel Blends and Di-Ethyl-Ether on the Cold Starting Performance of a Compression Ignition Engine. *Energies*, 9, 284. <https://doi.org/10.3390/en9040284>
- Dharmawan, A. H., Fauzi, A., Putri, E. I. K., Pacheco, P., Dermawan, A., Nuva, N., Amalia, R., & Sudaryanti, D. A. (2020). Bioenergy policy: The biodiesel sustainability dilemma in Indonesia [Article]. *International Journal of Sustainable Development and Planning*, 15(4), 537-546. <https://doi.org/10.18280/ijstdp.150414>

- E, J., Pham, M., Deng, Y., Nguyen, T., Duy, V., Le, D., Zuo, W., Peng, Q., & Zhang, Z. (2018, 2018/04/15/). Effects of injection timing and injection pressure on performance and exhaust emissions of a common rail diesel engine fueled by various concentrations of fish-oil biodiesel blends. *Energy*, 149, 979-989. <https://doi.org/https://doi.org/10.1016/j.energy.2018.02.053>
- Elkelawy, M., Alm-Eldin Bastawissi, H., El Shenawy, E. A., Taha, M., Panchal, H., & Sadasivuni, K. K. (2020). Study of performance, combustion, and emissions parameters of DI-diesel engine fueled with algae biodiesel/diesel/n-pentane blends [Article]. *Energy Conversion and Management: X*, Article 100058. <https://doi.org/10.1016/j.ecmx.2020.100058>
- Erdiwansyah, E., Mamat, R., Sani, M. S. M., Khoerunnisa, F., Sardjono, R. E., Ali, O., & Ibrahim, T. (2018). Effects of Diesel-Biodiesel Blends in Diesel Engine Single Cylinder on the Emission Characteristic. *MATEC Web of Conferences*,
- Fridstrøm, L., & Østli, V. (2021). Direct and cross price elasticities of demand for gasoline, diesel, hybrid and battery electric cars: the case of Norway [Article]. *European Transport Research Review*, 13(1), Article 3. <https://doi.org/10.1186/s12544-020-00454-2>
- Ganapathy, T., Gakkhar, R. P., & Murugesan, K. (2011). Influence of injection timing on performance, combustion and emission characteristics of Jatropha biodiesel engine [Article]. *Applied Energy*, 88(12), 4376-4386. <https://doi.org/10.1016/j.apenergy.2011.05.016>
- Gao, J. B., Chen, H. B., Dave, K., Chen, J. Y., & Jia, D. Y. (2020, May). Fuel economy and exhaust emissions of a diesel vehicle under real traffic conditions [Article]. *Energy Science & Engineering*, 8(5), 1781-1792. <https://doi.org/10.1002/ese3.632>
- Gouveia, L., Oliveira, A. C., Congestri, R., Bruno, L., Soares, A. T., Menezes, R. S., Filho, N. R. A., & Tzovenis, I. (2017). 10 - Biodiesel from microalgae. In C. Gonzalez-Fernandez & R. Muñoz (Eds.), *Microalgae-Based Biofuels and Bioproducts* (pp. 235-258). Woodhead Publishing. <https://doi.org/https://doi.org/10.1016/B978-0-08-101023-5.00010-8>
- Heywood, P. J. (1988). *Internal Combustion Engine Fundamentals*. McGraw-Hill Education. <https://books.google.com.my/books?id=u9FSAAAAMAAJ>

- Hlavacova, Z., Božiková, M., Hlaváč, P., Regrut, T., & Ardonová, V. (2018, 01/01). Selected physical properties of various diesel blends. *International Agrophysics*, 32. <https://doi.org/10.1515/intag-2016-0095>
- How, H. G., Masjuki, H. H., Kalam, M. A., & Teoh, Y. H. (2018). Influence of injection timing and split injection strategies on performance, emissions, and combustion characteristics of diesel engine fueled with biodiesel blended fuels [Article]. *Fuel*, 213, 106-114. <https://doi.org/10.1016/j.fuel.2017.10.102>
- Hu, M. (2020). The Current Status of Hydrogen and Fuel Cell Development in China. *Journal of Electrochemical Energy Conversion and Storage*, 17(3). <https://doi.org/10.1115/1.4045702>
- Ibrahim, S., Abed, K., Gad, M., & Abu Hashish, H. (2020, 02/01). Experimental Study on the Effect of Preheated Egyptian Jatropha Oil and Biodiesel on the Performance and Emissions of a Diesel Engine. *International Journal of Mechanical & Mechatronics Engineering*, 20, 59-69.
- John, B. H. (2018). *Internal Combustion Engine Fundamentals*, Second Edition (2nd edition. ed.). McGraw-Hill Education. <https://www.accessengineeringlibrary.com/content/book/9781260116106>
- Kaya, C., & Kökkülünk, G. (2020). Biodiesel as alternative additive fuel for diesel engines: An experimental and theoretical investigation on emissions and performance characteristics. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 1-23. <https://doi.org/10.1080/15567036.2020.1774685>
- Khalid, A., Tajuddin, A., Jaat, M., Manshoor, B., Zaman, I., Uthm, S., & Nursal, R. (2017, 06/30). Performance and emissions of diesel engine fuelled with preheated biodiesel fuel derived from crude palm, jatropha, and waste cooking oils. *International Journal of Automotive And Mechanical Engineering*, 14, 4273-4284. <https://doi.org/10.15282/ijame.14.2.2017.12.0341>
- Kodate, S. V., Yadav, A. K., & Kumar, G. N. (2020, 2020/09/01). Combustion, performance and emission analysis of preheated KOME biodiesel as an alternate fuel for a diesel engine. *Journal of Thermal Analysis and Calorimetry*, 141(6), 2335-2345. <https://doi.org/10.1007/s10973-020-09814-5>

- Kotaiah, K., Periyasamy, P., & Prabhakar, M. (2020). Performance and Emission Characteristics of VCR Diesel Engine with Pre Heated Lemon Grass Biodiesel as Fuel. *IOP Conference Series: Materials Science and Engineering*,
- Lešnik, L., Kegl, B., Torres-Jiménez, E., & Cruz-Peragón, F. (2020, 2020). Why we should invest further in the development of internal combustion engines for road applications. *Oil & Gas Science and Technology - Revue d'IFP Energies nouvelles*, 75, 56. <https://doi.org/10.2516/ogst/2020051>
- Lewiski, F. V., Bazzo, E., Martins, M. E. S., Machado, P. R. M., Antolini, J., Prante, G. A. F., & Cogo, V. V. (2017). Performance and Emissions Analysis of a Diesel Engine Fueled with Pre-Heated Soybean Oil <https://doi.org/10.4271/2017-36-0215>
- Ligan Noukpo, M., Ngayihi Abbe, C. V., Nkongho Anyi, J., Essola, D., Mezoue, C., Mouangue, R., & Nzengwa, R. (2020, 2020/12/03). Experimental and Numerical Investigation on the Influence of the Rate of Injection (Roi) on Engine Performance for B100 Fuel Control Strategy in Diesel Engines. *Journal of Engineering*, 2020, 8884754. <https://doi.org/10.1155/2020/8884754>
- Liu, H.-P., Strank, S., Werst, M., Hebner, R., & Osara, J. (2010). Combustion Emissions Modeling and Testing of Neat Biodiesel Fuels (Vol. 1). <https://doi.org/10.1115/ES2010-90038>
- Lopes, S. M., Furey, R., & Geng, P. (2013). Calculation of Heating Value for Diesel Fuels Containing Biodiesel. *SAE International Journal of Fuels and Lubricants*, 6(2), 407-418. <http://www.jstor.org/stable/26273015>
- Mohapatra, A. K., Senapati, A. K., Jha, G., Sharma, C. K., & Kumar, P. (2019). Preheating of sunflower blended biodiesel for the improvement of performance characteristics of a DI diesel engine under various loads [Article]. *International Journal of Engineering and Advanced Technology*, 8(6), 921-926. <https://doi.org/10.35940/ijeat.F8228.088619>
- Muhammad Usman, K., Abubakar, S., Umaru, S., Balasubramanian, D., Shameer, P. M., Nishath, P., Kannan, S., & Senophiya, M. (2018). Comparative Analysis of Experimental and Simulated Performance and Emissions of Compression Ignition Engine Using Biodiesel Blends.
- Muthuraman, S., Sivaraj, M., & Rajkumar, S. (2020, Oct 15-16). Performance analysis of compression ignition (CI) engine using biodiesel. [Materials today-

- proceedings]. International Conference on Newer Trends and Innovations in Mechanical Engineering (ICONTIME) - Materials Science, Electr Network.
- Nabi, M. N., Zare, A., Hossain, F. M., Ristovski, Z. D., & Brown, R. J. (2017, Nov). Reductions in diesel emissions including PM and PN emissions with diesel-biodiesel blends. *Journal of Cleaner Production*, 166, 860-868. <https://doi.org/10.1016/j.jclepro.2017.08.096>
- Özgül, E., & Bedir, H. (2019). Fast NO_x emission prediction methodology via one-dimensional engine performance tools in heavy-duty engines [Article]. *Advances in Mechanical Engineering*, 11(4). <https://doi.org/10.1177/1687814019845954>
- Park, H., Bae, C., & Ha, C. (2019, 2019/11/01/). A comprehensive analysis of multiple injection strategies for improving diesel combustion process under cold-start conditions. *Fuel*, 255, 115762. <https://doi.org/https://doi.org/10.1016/j.fuel.2019.115762>
- Pauly, J., Kouakou, A. C., Habrioux, M., & Le Mapihan, K. (2014, 2014/12/01/). Heat capacity measurements of pure fatty acid methyl esters and biodiesels from 250 to 390K. *Fuel*, 137, 21-27. <https://doi.org/https://doi.org/10.1016/j.fuel.2014.07.037>
- Prieto, N. M. C. T., Ferreira, A. G. M., Portugal, A. T. G., Moreira, R. J., & Santos, J. B. (2015, 2015/02/01/). Correlation and prediction of biodiesel density for extended ranges of temperature and pressure. *Fuel*, 141, 23-38. <https://doi.org/https://doi.org/10.1016/j.fuel.2014.09.113>
- Priyadarshi, D., & Paul, K. K. (2018, 07/23). Engine Performance and Emission study of Waste cooking oil and Sewage sludge derived Biodiesel blend. *IOP Conference Series: Earth and Environmental Science*, 167, 012035. <https://doi.org/10.1088/1755-1315/167/1/012035>
- Rami Reddy, S., Murali, G., Ahamad Shaik, A., Dhana Raju, V., & Sreekara Reddy, M. B. S. (2021). Experimental evaluation of diesel engine powered with waste mango seed biodiesel at different injection timings and EGR rates [Article]. *Fuel*, 285, Article 119047. <https://doi.org/10.1016/j.fuel.2020.119047>
- Ramírez-Verduzco, L. F., García-Flores, B. E., Rodríguez-Rodríguez, J. E., & del Rayo Jaramillo-Jacob, A. (2011, 2011/05/01/). Prediction of the density and viscosity in biodiesel blends at various temperatures. *Fuel*, 90(5), 1751-1761. <https://doi.org/https://doi.org/10.1016/j.fuel.2010.12.032>

- S R, T., Chandrashekar, K., Yogish, H., & Mahesha, A. M. (2018, 02/28). Investigation of Effect of Injection Pressure on Performance and Emission Characteristics of Composite Oil Biodiesel on DI CI Engine. *International Journal of Mechanical and Production Engineering Research and Development*, 8, 1287-1298. <https://doi.org/10.24247/ijmperdfeb2018149>
- Said, M., Abdul Aziz, A., & Muhamad Said, M. F. (2012, 06/01). Effect of Palm Methyl Ester - Diesel Blends Performance and Emission of a Single-Cylinder Direct-Injection Diesel Engine. *AIP Conference Proceedings*, 1440, 562-570. <https://doi.org/10.1063/1.4704263>
- Said, N. H., Ani, F. N., & Said, M. F. M. (2018). Emission and performance characteristics of waste cooking oil biodiesel blends in a single direct injection diesel engine [Article]. *International Journal of Technology*, 9(2), 238-245. <https://doi.org/10.14716/ijtech.v9i2.1204>
- Sawant, P., Warstler, M., & Bari, S. (2018). Exhaust Tuning of an Internal Combustion Engine by the Combined Effects of Variable Exhaust Pipe Diameter and an Exhaust Valve Timing System. *Energies*, 11(6), 1545. <https://www.mdpi.com/1996-1073/11/6/154>
- Setiawan, Y. (2019). *Produksi dan Uji Kinerja Biodiesel dengan Bahan Baku Minyak Goreng Bekas Atma Jaya Catholic University*.
- Shammut, M., Cao, M., Zhang, Y., Papaix, C., Liu, Y., & Gao, X. (2019). Banning diesel vehicles in London: Is 2040 too late? [Article]. *Energies*, 12(18), Article 3495. <https://doi.org/10.3390/en12183495>
- Subramanian, K. A. (2018). *Biofuelled Reciprocating Internal Combustion Engines*. Taylor & Francis.
- Technologies, G. (2016). *Engine Performance Application Manual*.
- Trindade, M. (2018). *Increased Biodiesel Efficiency Alternatives for Production, Stabilization, Characterization and Use of Coproduct: Alternatives for Production, Stabilization, Characterization and Use of Coproduct*. <https://doi.org/10.1007/978-3-319-73552-8>
- Tziourtzioumis, D., & Stamatelos, T. (2017, 07/11). Experimental Investigation of the Effect of Biodiesel Blends on a DI Diesel Engine's Injection and Combustion. *Energies*, 10. <https://doi.org/10.3390/en10070970>

- Vijay Kumar, M., Veeresh Babu, A., & Ravi Kumar, P. (2018, 2018/03/01/). The impacts on combustion, performance and emissions of biodiesel by using additives in direct injection diesel engine. *Alexandria Engineering Journal*, 57(1), 509-516. <https://doi.org/https://doi.org/10.1016/j.aej.2016.12.016>
- Vijayagopal, R., & Rousseau, A. (2021). Electric Truck Economic Feasibility Analysis. *World Electric Vehicle Journal*, 12(2), 75. <https://www.mdpi.com/2032-6653/12/2/75>
- Wahyono Y, H. H., Budihardjo MA, Adiansyah JS. (2020). Assessing the Environmental Performance of Palm Oil Biodiesel Production in Indonesia: A Life Cycle Assessment Approach. *Energies*, 13, Article 3248.
- Wang, S., Karthickeyan, V., Sivakumar, E., & Lakshmikandan, M. (2020). Experimental investigation on pumpkin seed oil methyl ester blend in diesel engine with various injection pressure, injection timing and compression ratio [Article]. *Fuel*, 264, Article 116868. <https://doi.org/10.1016/j.fuel.2019.116868>
- Xue, J., Grift, T. E., & Hansen, A. C. (2011, 2011/02/01/). Effect of biodiesel on engine performances and emissions. *Renewable and Sustainable Energy Reviews*, 15(2), 1098-1116. <https://doi.org/https://doi.org/10.1016/j.rser.2010.11.016>
- Yoon, S. K., Ge, J. C., & Choi, N. J. (2019). Influence of fuel injection pressure on the emissions characteristics and engine performance in a CRDI diesel engine fueled with palm biodiesel blends [Article]. *Energies*, 12(20), Article 3837. <https://doi.org/10.3390/en12203837>

LIST OF PUBLICATIONS

Indexed Conference Proceedings

Setiawan, Yosua, Said, M. F. M. (2022). Simulation study on the effect of injection pressure on single cylinder diesel engine fuelled with biodiesel blend. In *International Conference on Sustainable Engineering & Advanced Technology 2022(ICSEAT 2022)*. (**Indexed by SCOPUS**)