Experimental Investigations of Palm Oil Biodiesel Operated in a DI Diesel Engine

N.Navaneetha Krishnan[1*], S.Paulraj[1], C.Arivazhagan[1], M.Bharanikumar[1], Silambarasan Rajendran[2,4], Ruby Pant[3],
[1]Department of Automobile Engineering, Annapoorana Engineering College (Autonomous), Salem, 636308, Tamil Nadu, India.
[2]Department of Mechanical Engineering, Annapoorana Engineering College (Autonomous), Salem, 636308, Tamil Nadu, India.
[3]Department of Mechanical Engineering, Uttaranchal Institute of Technology, Uttaranchal University, Uttarakhand, 248007.
.[4]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India.
*Corresponding author: krishnaan5454@gmail.com

Abstract

The growing demand for sustainable energy sources and stringent emission regulations have intensified research on renewable fuels for compression ignition (CI) engines. Among various alternatives, palm oil biodiesel has gained considerable attention due to its high availability, biodegradability, and compatibility with existing diesel engine infrastructure. In this study, experimental investigations were conducted to evaluate the performance and emission characteristics of palm oil biodiesel and its blends in a single-cylinder, four-stroke direct injection (DI) diesel engine operating at constant speed under varying load conditions. Fuel blends including B20, B40, and B100 were tested and compared with conventional diesel. Key performance parameters such as brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC), along with emission characteristics including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and smoke opacity were analyzed. The results indicate that biodiesel blends exhibit slightly lower BTE and higher BSFC compared to diesel due to their lower calorific value and higher viscosity. However, significant reductions in CO, HC, and smoke emissions were observed owing to the oxygenated nature of biodiesel, which enhances combustion efficiency. A marginal increase in NOx emissions was recorded with higher biodiesel content, attributed to elevated in-cylinder combustion temperatures.Among the tested fuels, the B20 blend demonstrated the best compromise between engine performance and emission reduction. The findings confirm that palm oil biodiesel can be effectively utilized in DI diesel engines without major modifications, offering a viable and environmentally sustainable alternative to conventional diesel fuel.

Keywords:

Palm oil biodiesel; Direct injection diesel engine; Brake thermal efficiency; Brake specific fuel consumption; Exhaust emissions; Carbon monoxide (CO); Hydrocarbon (HC); Nitrogen oxides (NOx); Smoke opacity; Renewable fuels.

Introduction

The rapid depletion of fossil fuel reserves and the growing concerns over environmental pollution have accelerated the search for renewable and sustainable alternative fuels for internal combustion engines. Diesel engines, widely used in transportation, agriculture, and power generation sectors, are known for their high thermal efficiency and durability. However, conventional diesel combustion contributes significantly to greenhouse gas emissions, particulate matter, nitrogen oxides (NOx), and other harmful pollutants. Therefore, identifying cleaner and renewable substitutes that can be used in existing diesel engines without major modifications is of paramount importance [1]. Biodiesel has emerged as a promising alternative fuel for compression ignition (CI) engines. It is a renewable, biodegradable, non-toxic fuel derived from vegetable oils or animal fats through a transesterification process. The process reduces the high viscosity of raw oils and converts them into fatty acid methyl esters (FAME), which possess properties comparable to diesel fuel. Biodiesel contains inherent oxygen content (approximately 10–12%), which promotes more complete combustion and reduces carbon monoxide (CO), hydrocarbon (HC), and smoke emissions [2]. Among various feedstocks, palm oil is considered one of the most suitable sources for biodiesel production due to its high oil yield, year-round availability, and established agricultural infrastructure in tropical countries. Palm oil biodiesel exhibits a higher cetane number, better lubricity, and higher flash point compared to petroleum diesel, enhancing engine safety and combustion quality. However, its relatively higher viscosity and lower calorific value may slightly affect engine performance and fuel consumption [3]. Previous studies have reported that biodiesel blends, particularly B20 (20% biodiesel + 80% diesel), provide a good balance between engine performance and emission reduction. While reductions in CO, HC, and smoke emissions are consistently observed, a slight increase in NOx emissions is commonly reported due to higher combustion temperatures and oxygen availability in biodiesel fuels [4]. The utilization of biodiesel in compression ignition (CI) engines has been extensively investigated over the past two decades due to increasing environmental concerns and depletion of fossil fuels. Numerous studies have evaluated the performance, combustion, and emission characteristics of various biodiesel feedstocks in direct injection (DI) diesel engines [5]. Early investigations on biodiesel as an alternative fuel reported that vegetable oil methyl esters could be used in diesel engines with minimal or no engine modifications. Researchers observed that biodiesel blends generally exhibit slightly lower brake thermal efficiency (BTE) compared to diesel because of their lower calorific value. However, improved combustion characteristics due to higher cetane number and oxygen content were also reported [6]. Studies on palm oil biodiesel specifically have shown promising results. Experimental investigations demonstrated that palm oil methyl ester (POME) provides smoother engine operation and enhanced lubricity. The higher cetane number of palm biodiesel contributes to shorter ignition delay and more stable combustion. However, its higher density and viscosity may lead to inferior atomization at higher blending ratios, slightly affecting performance [7]. Several researchers have reported that B20 blends offer an optimal balance between efficiency and emission control. In most cases, B20 showed performance characteristics very close to neat diesel while significantly reducing carbon monoxide (CO), hydrocarbon (HC), and smoke emissions. The presence of oxygen in biodiesel molecules enhances oxidation of fuel-rich zones, thereby reducing incomplete combustion products [8]. Emission characteristics have been a primary focus in biodiesel research. A consistent reduction in CO and HC emissions has been observed with increasing biodiesel concentration. Smoke opacity and particulate matter emissions also decrease due to reduced aromatic content and enhanced oxygen availability. However, many studies have reported a marginal increase in nitrogen oxides (NOx) emissions. This increase is attributed to higher in-cylinder temperatures, advanced combustion phasing, and oxygen enrichment during combustion [9]. Combustion analysis conducted by various researchers indicates that biodiesel fuels generally show higher peak cylinder pressure and heat release rates during premixed combustion phase due to shorter ignition delay. Some studies have suggested that optimizing injection timing or employing exhaust gas recirculation (EGR) can effectively mitigate NOx emissions associated with biodiesel use [10]. Recent advancements include the addition of nanoparticles, alcohol blends, and hydrogen enrichment to biodiesel in order to further enhance performance and reduce emissions. These hybrid approaches have demonstrated improvements in brake thermal efficiency and reductions in smoke and NOx under certain operating conditions [11]. Although extensive work has been carried out on biodiesel fuels, variations in feedstock properties, engine type, operating conditions, and blend ratios result in differing outcomes. Therefore, continuous experimental validation under specific engine configurations remains necessary. In this context, the present study aims to provide a detailed experimental evaluation of palm oil biodiesel blends in a single-cylinder DI diesel engine, contributing further insight into its practical feasibility and emission behavior [12]. Despite extensive research on biodiesel, there is a continuous need to evaluate its performance under different operating conditions and blending ratios, particularly in direct injection (DI) diesel engines that are widely used

in practical applications. Therefore, the present study aims to experimentally investigate the performance and emission characteristics of palm oil biodiesel and its blends (B20, B40, and B100) in a single-cylinder DI diesel engine under varying load conditions. The outcomes of this research will contribute to assessing the feasibility of palm oil biodiesel as a sustainable alternative fuel for diesel engine applications.

2. Materials and Methods

2.1 Palm Oil Biodiesel

Palm oil biodiesel used in this study was produced through the transesterification process. Refined palm oil was reacted with methanol in the presence of a suitable alkaline catalyst (NaOH/KOH) under controlled temperature and stirring conditions. The reaction converted triglycerides into fatty acid methyl esters (FAME) and glycerol as a by-product. After separation, washing, and drying, the final palm oil methyl ester (POME) was obtained and stored in airtight containers. The fuel properties of diesel and palm oil biodiesel were measured according to ASTM standards. Important properties such as density, kinematic viscosity, calorific value, flash point, and cetane number were evaluated before engine testing.

Figure 1 Palm oil

Table 1.Fuel characteristics of hydrogen, palm oil , and diesel

S.No	Property	Diesel	Palm oil
1	Molecular weight (gm/mol)	160	918.54
2	Stoichiometric air fuel ratio	33.5	N/A
3	Flame velocity (cm/s)	27	34
4	Auto-ignition temperature (K)	534	700-830
5	Heat of combustion (kJ/kg)	40.3	64
6	Density of gas at NTP (g/cm^3)	0.85	0.74
7	Octane number	-	55
8	Cetane number	45-55	45
9	Boiling point (K)	550-630	340 - 405
10	Specific gravity	0.78	0.918

3. Experimental Setup

The most popular engine used for agricultural pump sets, farm machinery and medium scale testing is Kirloskar brand engine, which is one of the oldest brands. It has the features such as sturdiness at high pressure with rugged structure. Engine modifications such as varying the injection timing, injection pressure, and compression ratio are easily possible with this type of engine. Moreover assembling and dismantling the engine are easy. Water cooled, naturally aspirated, single cylinder, four stroke direct injection compression ignition engine was used for this investigation. It had a displacement volume of 661 cc and compression ratio of 17.5:1. The engine developed 5.9 kW at 1800 rpm. The load variation had been done at the rate of20%, 40%, 60%, 80%, and 100%. The fuel injection pressure was 200 bar and the manufacturer had set injection timing at 27o before TDC. The engine had a combustion chamber with overhead valves operated by push rods. Water jackets were provided in the engine block to manage the cooling of the engine. A governor was used to maintain a constant speed even though the load was varied which also controlled the fuel flow. A hole was drilled and necessary provision was made to fix a piezoelectric pressure sensor to give the feedback signal of the in-cylinder pressure. An eddy current dynamometer was coupled with the engine to apply the load to the engine.
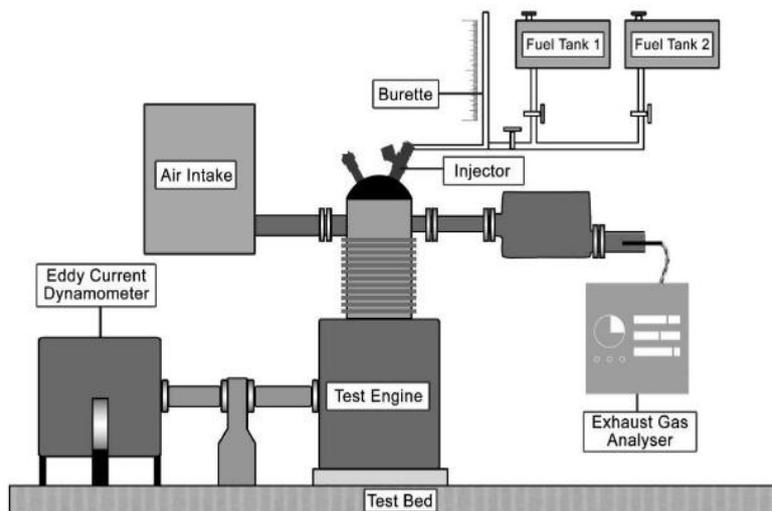

Figure 2. Experimental setup

Brake Thermal Efficiency

Figure 3 depicts the fluctuation of brake thermal efficiency with brake power for various biodiesel mixes. At all power outputs, it was discovered that biodiesel blends had worse brake thermal efficiency than diesel. The calorific value of the fuel determines how much energy is used and how much braking power is applied to the diesel engine. Based on research findings, it was determined that biodiesel will have higher BTE rates than mineral diesel due to its higher oxygen content and better fuel-rich combustion.Due to larger fuel droplet size, a greater fuel density, a higher fuel presence in the combustion chamber, deprived atomization, and less volatile fuel, the test fuel blends Diesel (27.84%), B20 (28.67%), and B100 (23.18%) had a minimum rate of BTE at higher load compared to diesel.
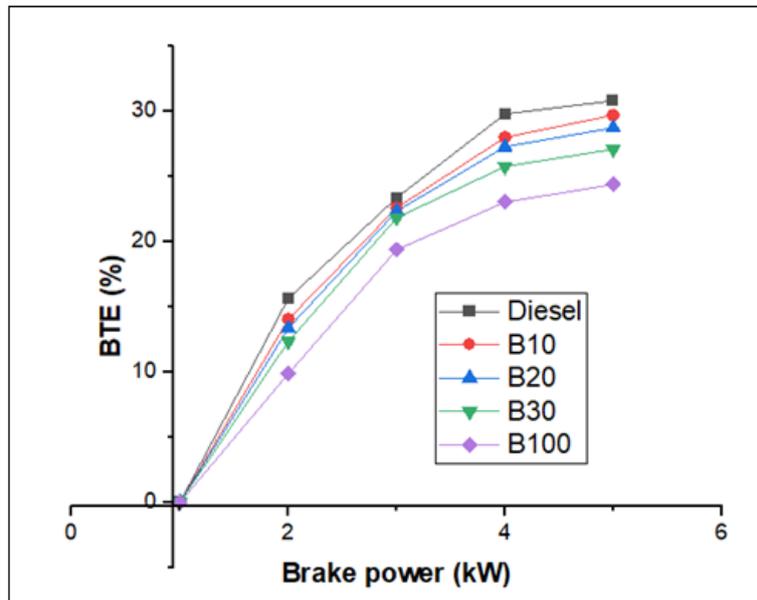

Figure 3 BTE Vs Brake power

Brake specific energy consumption

Figure 4 depicts the fluctuation of brake specific fuel consumption with brake power for various biodiesel mixes. Brake specific fuel consumption falls with increasing load. When compared to diesel, it has been found that biodiesel mixes have greater brake specific fuel consumption. A higher calorific value of a fuel will result in a higher rate of evaporation, thereby improving combustion. Because biodiesel blends are less calorific than diesel, they evaporate more slowly. Slower evaporation rates increase the amount of fuel required for the brakes.
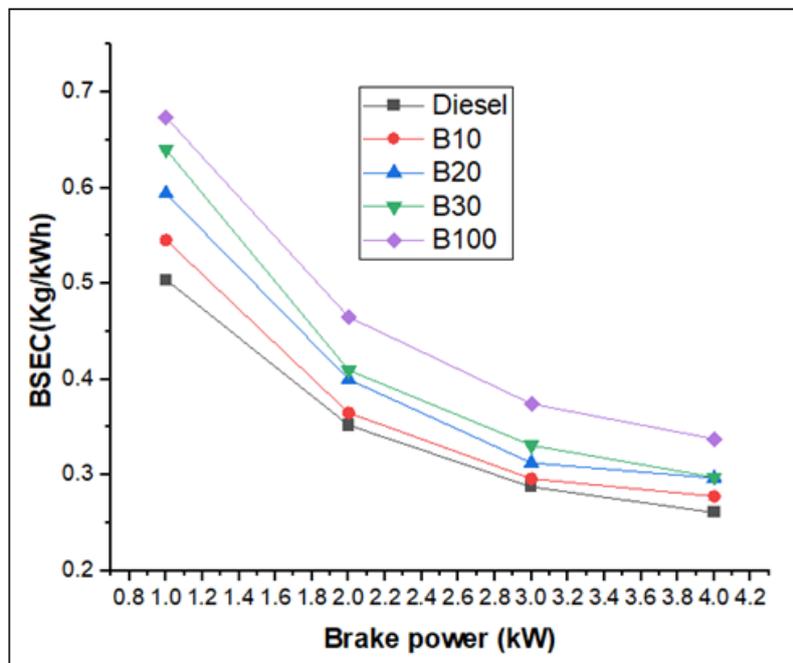

Figure 4 BSEC Vs Brake power

Carbon monoxide emission

Figure 5 illustrates how carbon monoxide emissions change as a function of brake power for various biodiesel mixes. Compared to biodiesel mixes, plain diesel produces less carbon monoxide emissions. This is mostly caused by the increased viscosity of biodiesel mixes, which causes incomplete combustion due to poor fuel and air mixing
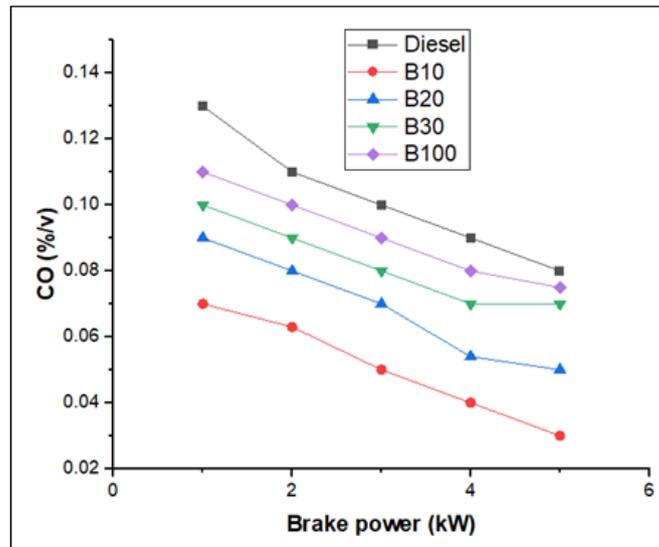
Figure 4 Carbon monoxide Vs Brake power

Unburned hydrocarbon emission

Figure 5 depicts the change of hydrocarbon emissions with brake power for various biodiesel mixes. Compared to biodiesel mixes, plain diesel emits fewer hydrocarbons into the atmosphere. This is primarily caused by the increased viscosity of biodiesel mixes, which results in inadequate fuel-air mixing and inefficient combustion
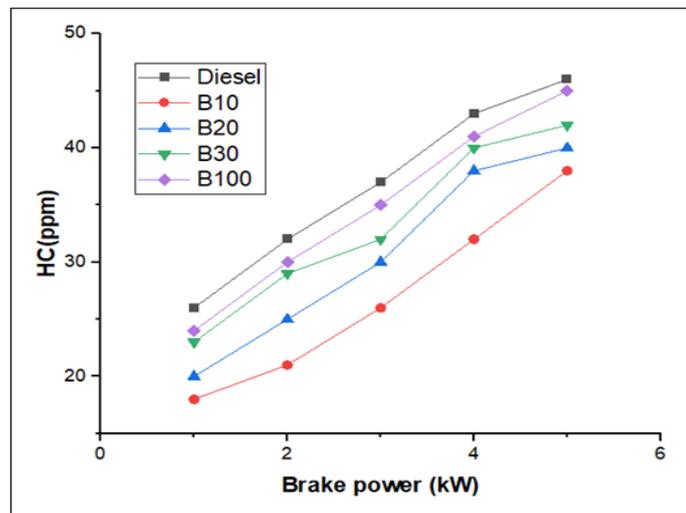

Figure 5 Hydrocarbon Vs Brake power

Oxides of nitrogen emission

Figure 6 depicts how Nitrogen Oxide emissions change as a function of brake power for various biodiesel mixes. Compared to biodiesel mixes, plain diesel emits a greater level of nitrogen oxides. Diesel has a larger calorific value and lower viscosity than biodiesel mixes, which is mostly to blame for this. This leads to improved fuel and air mixing, which promotes full fuel combustion. When fuel is totally burnt, it results in more nitrogen oxide emissions than when biodiesel blends are utilized because it raises exhaust gas temperature and peak pressure increase rate more quickly
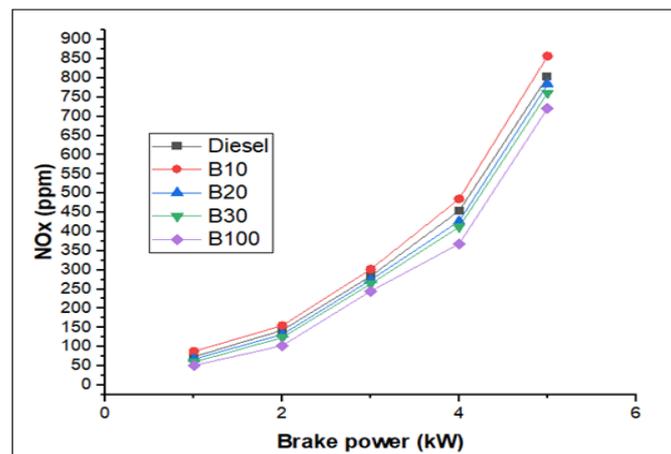

Figure 6 Oxides of Nitrogen Vs Brake power

Smoke emission

Figure 7 depicts the fluctuation of Smoke Opacity with Brake Power for several biodiesel mixes. Comparing neat diesel to biodiesel mixes, the neat diesel has less smoke opacity. This is because greater viscosity biodiesel mixes result in poorer fuel atomization, which raises smoke emissions
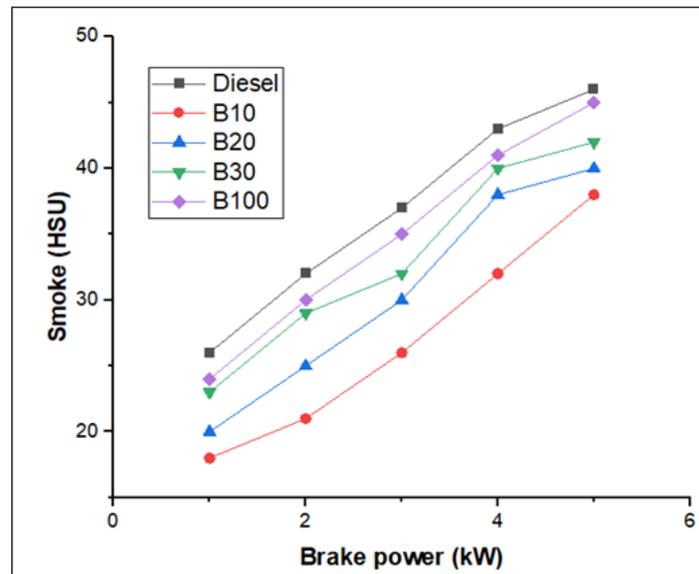

Figure 7 Smoke Vs Brake power

Conclusion

In this research work, Palm Oil was extracted from Palm plants, transesterified to produce Palm oil biodiesel. This was mixed in volumetric proportions with neat diesel and four types of blends B20, B40, B50, B100. Four phases of experiments were conducted to investigate the performance, combustion, and emission characteristics.

➤ Almost same power output is noticed in all blends with slightly reduced thermal efficiency, because of reduced calorific values of the bio diesel fuels.

➤ The engine performance with bio diesel up to B20 blends was nearly similar to that of diesel. Slightly higher specific fuel consumption was observed at full load for B20.

➤ At the maximum load condition, the B20 blend exhibits better BTE in comparison to other test fuels. As BSEC increased by 1.93% compared to diesel at maximal power production, it reduced BTE by 1.78%.

➤ Compared to diesel, the B20 blend decreased unburned HC by 7.13%, unburned CO by 16.27%, and smoke opacity by 8.13 at maximum power output. It may be as a result of the ignition delay time being shortened, the rich oxygen content, and better fuel characteristics

➤ However, compared to diesel, the NOx emission with the B20 blends was greater by 2.10%. The availability of oxygen, elevated in-cylinder gas temperatures, and delayed ignition at the greatest load conditions are the main factors contributing to the rise in NOx emissions.

Based on the results of this exhaustive experimental analysis, a B20 blend can be used as an alternative fuel source for a stock diesel engine. With better fuel combustion and performance characteristics, tailpipe emissions are significantly reduced.

Reference

1. Agarwal, A. K. (2007). Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. *Progress in Energy and Combustion Science, 33*(3), 233–271. https://doi.org/10.1016/j.pecs.2006.08.003
2. Atabani, A. E., Silitonga, A. S., Ong, H. C., Mahlia, T. M. I., Masjuki, H. H., Badruddin, I. A., & Fayaz, H. (2013). Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. *Renewable and Sustainable Energy Reviews, 18*, 211–245. https://doi.org/10.1016/j.rser.2012.10.013
3. Banapurmath, N. R., Tewari, P. G., & Hosmath, R. S. (2008). Performance and emission characteristics of a DI compression ignition engine operated on Honge, Jatropha and sesame oil methyl esters. *Renewable Energy, 33*(9), 1982–1988. https://doi.org/10.1016/j.renene.2007.11.012
4. Demirbas, A. (2009). Biodiesel from waste cooking oil via base-catalytic and supercritical methanol transesterification. *Energy Conversion and Management, 50*(4), 923–927. https://doi.org/10.1016/j.enconman.2008.12.023
5. Ganapathy, T., Murugesan, K., & Gakkhar, R. P. (2011). Performance optimization of Jatropha biodiesel engine model using Taguchi approach. *Applied Energy, 88*(12), 4377–4386. https://doi.org/10.1016/j.apenergy.2011.05.012
6. Heywood, J. B. (2018). *Internal combustion engine fundamentals* (2nd ed.). McGraw-Hill Education.
7. 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 biodiesel. *Energy, 36*(1), 397–402. https://doi.org/10.1016/j.energy.2010.10.026
8. Lapuerta, M., Armas, O., & Rodríguez-Fernández, J. (2008). Effect of biodiesel fuels on diesel engine emissions. *Progress in Energy and Combustion Science, 34*(2), 198–223. https://doi.org/10.1016/j.pecs.2007.07.001
9. Lin, C.-Y., & Li, R.-J. (2009). Engine performance and emission characteristics of marine fish-oil biodiesel produced from the discarded parts of marine fish. *Fuel Processing Technology, 90*(7–8), 883–888. https://doi.org/10.1016/j.fuproc.2009.03.007
10. Ozsezen, A. N., & Canakci, M. (2011). Determination of performance and combustion characteristics of a diesel engine fueled with canola and waste palm oil methyl esters. *Energy Conversion and Management, 52*(1), 108–116. https://doi.org/10.1016/j.enconman.2010.06.049
11. Ramadhas, A. S., Jayaraj, S., & Muraleedharan, C. (2005). Biodiesel production from high FFA rubber seed oil. *Fuel, 84*(4), 335–340. https://doi.org/10.1016/j.fuel.2004.09.016
12. Sahoo, P. K., & Das, L. M. (2009). Combustion analysis of Jatropha, Karanja and Polanga based biodiesel as fuel in a diesel engine. *Fuel, 88*(6), 994–999. https://doi.org/10.1016/j.fuel.2008.11.012
13. Silitonga, A. S., Masjuki, H. H., Mahlia, T. M. I., Ong, H. C., Chong, W. T., & Boosroh, M. H. (2013). Overview properties of biodiesel diesel blends from edible and non-edible feedstock. *Renewable and Sustainable Energy Reviews, 22*, 346–360. https://doi.org/10.1016/j.rser.2013.01.055
14. Sundus, F., Fazal, M. A., & Masjuki, H. H. (2017). Tribology with biodiesel: A study on enhancing biodiesel stability and its fuel properties. *Renewable and Sustainable Energy Reviews, 70*, 399–412. https://doi.org/10.1016/j.rser.2016.11.217
15. Yusop, A. F., Mamat, R., Yusaf, T., Najafi, G., & Yasin, M. H. M. (2018). Analysis of particulate matter (PM) emissions in diesel engines using palm oil biodiesel blended fuels. *Renewable Energy, 118*, 324–332. https://doi.org/10.1016/j.renene.2017.11.060