SEMARAK ILMU PUBLISHING

Semarak Engineering Journal

Journal homepage:
https://semarakilmu.com/
ISSN: 3036-0145



Particle Size Distribution Emitted from Combustion of Diesel- Waste Cooking Oil Biodiesel Blends

Noora S. Ekab[1,*], Miqdam T. Chaichan[2], Ghassan A. Bilal[2], Mohammed A. Fayad[2], Ahmed H. Janabi[3], Hasan Ali Jebur Abo Dihin[3], Ali Al-Mahmood[3]

[1] Elctromechanical Engineering Department, University of Technology- Iraq, Baghdad, Iraq
[2] Energy and Renewable Energies Technology Center, University of Technology- Iraq, Baghdad 10001, Iraq
[3] Computer Techniques, College of Engineering & Technology, Al-Mustaqbal University |Babylon, Iraq

ARTICLE INFO

Article history:
Received 20 July 2025
Received in revised form 29 November 2025
Accepted 10 December 2025
Available online 25 December 2025

Keywords:

Total suspended particles; biodiesel; sulfur; PM1; PM2.5; PM10

ABSTRACT

Iraqi diesel is characterized by its high sulfur content, which causes the emission of high concentrations of particulate matter. This work focuses on the evaluation of these particle size distribution when the engine is fuelled by pure diesel fuel blended with biodiesel. The study focused on particulates matters mass concentration. The first goal consists of monitoring the percentage of particulate matter substances emitted by the diesel engine powered with pure diesel fuel and biodiesel-diesel blends. The emissions of particles of all sizes decreased from biodiesel blends with a significant effect on particles measured in nano and fine particles. Under constant engine speed and variable load and, PM2.5 was reduced by 7.2%, 16.7%, 32.2% and 42.8% for DB20, DB35, DB50 and B100 compared to diesel, respectively. For the same testing conditions, the TSP reduced by 4.98%, 12.07%, 21.54% and 26.53%, respectively. The use of biodiesel blends also resulted in a significant reduction in particulate matter compared to diesel when the engine run at variable speed and fixed load. The reduction rate for PM1 was 12.13%, 36.65%, 60.92% and 81.06% for DB20, DB35, DB50 and B100, respectively. The PM10 reduced by 9%, 25.98%, 43% and 61.3%, respectively.

1. Introduction

Among the significant environmental degradation, air quality is of prominent importance nowadays. A large portion of air pollution is related to transportation, with the majority of engines operated with fossil fuels. Therefore, engines are working on biodiesel fuel formulations that are more efficient, reduce emissions and are environmentally and economically acceptable [1]. There is global pressure to develop new energy technologies that would enable a significant reduction in the use of fossil fuels in electricity production and transportation, in order to reduce the emission of gases responsible for increasing greenhouse gases and improve the quality of breathable air. To date, biodiesel and gasoline are examples in terms of engine performance in comparison with other

* *Corresponding author.*
E-mail address: 20112@uotechnology.edu.iq

alternative fuels that can be used in diesel engines, but they present the worst emissions of pollutants during their combustion [2].

In the particular case of diesel engines, the burning conditions of diesel fuel tend to form soot, which introduces health issues because the soot has direct impacts on human health [3]. The World Health Organization has classified diesel soot as a Group One human carcinogen, capable of causing lung cancer, and several epidemiological studies suggest a relationship between diesel soot and lung cancer in people who are exposed to this pollutant [4].

The discovery of the harmful effects of diesel engine emissions promotes the development of diesel engines and leads to the search for new fuels that meet the required reduction in harmful emissions. The use of biodiesel, and blends of biodiesel and diesel specifically developed for these types of engines, has been shown to achieve this requirement [5]. One problem with these alternative fuels compared to pure diesel is the magnitude of particulate emissions [6].

All methods used to date to reduce emissions from the combustion of conventional diesel fuel affect engine performance or fuel efficiency. Various combustion systems have been implemented to reduce emissions typically associated with high-performance diesel engines [7]. The best way to use heat requires maximum burn rate in range of 5 and 12 degrees ATDC (after top dead centre); this provides a balance between heat transfer, production and energy [8]. Also, the best optimal thermal efficiency range necessitates the combustion phases to fall within 5 and 12 degrees ATDC, ensuring the equilibrium in energy distribution among work output, exhaust energy, and heat transfer [9]. To overcome the combustion restrictions related to feed gas emissions, peak combustion pressures, pressure rise rate and, combustion is delayed towards the end of the expansion stroke by control the injection timing of fuel, coupled with the utilization of exhaust gas recirculation (EGR) [10,11]. EGR stands out as a highly efficient method for NOx reduction, yet its applicability is constrained by diminished efficiency of the combustion, slower combustion rates, and heightened soot emissions, all of which contribute to diminished fuel efficiency [12,13].

The basic problem with diesel engine emissions is that they contain harmful gases which create health and environmental hazards [14]. The diesel combustion process leads to high levels of particulate matters (PM) and unburned hydrocarbons (UHC) [15]. Dramatic emission reductions are mandatory in order to comply with legal restrictions and to reduce the environmental impact [16]. To achieve the near future goals set by any environmental legislation, more effort should be undertaken for the assessment and modelling of new technologies associated with pollutant emissions [17].

Nowadays, studies on the use of biodiesel are increasing day by day and are carried out in the field of toxicology, economy, social awareness, microbiology, and heat and mass transfer [18]. Meanwhile the CO_2 gas emitted during the operation of the engine is part of the carbon cycle in nature, other hazardous emissions contribute to global environmental problems such as air pollution, acid rains, the development of photochemical and harmful effects on human health [19]. The increase in the effect of greenhouse gases observed in the world in recent years has caused the difficulties of global warming and climate change to be brought to the agenda [20]. The farms can only convert the solar energy into oilseed and then biodiesel energy, and releasing the same amount of CO_2 that they consume from the atmosphere, due to the fact that they are di-Carboxy plants [21]. Significant information on the engine power and power capacity of biodiesel, which plays an important role in agriculture and land transportation systems, has been determined. However, the development in the reduction of gases such as CO, hydrocarbon (HC), nitrogen oxides (NOx), and PM that positively affect human health also remains as a significant solution to the concern of increasing the emissions [22].

Biodiesel is an alternative autochthonous, regenerated fuel and is considered as a clean energy source [23]. Biodiesel is produced from various feedstock like the oil of various crops, or waste or used oil that is obtained in food process plants or from fryers [24]. The most common source of biodiesel is vegetable oil, such as rapeseed oil, soybean oil, sunflower oil, corn oil, peanut oil, and safflower oil [25,26]. However, some biodiesels used in the experiments were derived from animal fats [27]. Biodiesel has a high flash point and low sulfur content, and is a biodegradable and renewable fuel [28]. Biodiesel blends do not require modifications in diesel engines. Previous studies [29,30] on biodiesel blending with diesel fuel have shown not so different performances in terms of engine efficiency and emissions. The advantage of biodiesel is that it has a high cetane number and does not contain sulfur. However, the main disadvantage of biodiesel is having a higher viscosity and density compared to diesel and a significant reduction in its calorific value [31,32]. Many researchers [33,34] have tried to blend biodiesel with diesel in different techniques to overcome the problem of low combustion temperature and improve performance of the engine. Most of them have concluded that the best blending ratio is B20 (a mixture of 20% biodiesel and 80% diesel), which improves density, cooling, calorific value and flash point, as well as increasing engine performance [35,36]. Lawan *et al*., [37] studied the effect of adding a biological material on the properties of biodiesel. The effectiveness of probiotic supplements depends on the level and type of phenolic compounds present in the additive and whether it contains antioxidants. Chaichan *et al*., [38] used oxygenated additives (ethanol and methanol) to diesel to investigate the performance and emission of the engine. The researchers studied several effects such as using 15% EGR, changing the equivalent ratio and injection timing. The study focused on the effect of these variables on both NOx and PM emissions. NOx levels increased with increasing equivalent ratio. Adding both E10 and M10 to diesel caused a reduction in PM levels, while EGR was shown to increase PM levels. In the case of combining oxygenated mixtures with EGR, PM emission levels were decreased. Using biodiesel that produced from crude and refined cooking oils and cooking waste results in an engine exhaust emission often depend on the fuel combustion process inside cylinder [39]. The difference in engine tailpipe emissions, such as the combustion characteristics of biodiesel and diesel fuel, can be significantly different [40]. Therefore, there will be an urgent need to evaluate both cylinder pressures as well as engine exhaust emissions to optimize diesel engine fuelling with biodiesel. In general, both edible and non-edible crude oils contain a higher amount of carbon, due to the glycerol compound found in the oil chains. Using these oils in a diesel engine would increase particulate matter significantly [41,42].

Further improvement of the technical and environmental properties of diesel fuel consisting of 20-35% biodiesel will enable an increase in the share of biodiesel in the world, the total volume of private biodiesel, the quantities of bioenergy resources, and the number of raw materials used [43, 44]. The United Nations and other international organizations have set goals to develop the production of environmentally friendly engine fuel, which is produced based on bioenergy resource. One of these goals is to find ways and means to produce biodiesel from available renewable animal and plant raw materials [45,46]. Commercially available oils and fats are the most economical. A biodiesel formulation derived from used restaurant oil was blended with Iraqi diesel, which has a high sulfur content. The tests were conducted under constant engine speed and variable loads. The experimental results indicated that incorporation of biodiesel (using volume ratios of 20%, 35% and 50%) into neat diesel resulted in an increase in brake fuel consumption by 2.6%, 5.9% and 7.35%, respectively. Moreover, when operating with a 50/50 biodiesel/diesel blend, emissions showed a significant decrease compared to pure diesel. For example, carbon monoxide (CO) levels decreased by 18%, hydrocarbons (HC) by 23.4%, nitrogen oxides (NOx) by 3.5%, fine particulate matter (PM) by 46.4%, hydrogen sulfide (H2S) by 47.5%, and finally, sulfur dioxide (SO2) decreased by 27.2% [47].

Based on a review of the recently published literature on biodiesel-fuelled diesel engines, the motivation of the study is to find a solution to the issue of the effect of engine load as an operating parameter on soot emitted from an internal combustion engine. The uniqueness of the study comes from the attempt to study a specific problem, which is the types of fine particles and their nanoscale dimensions emitted from blends of biodiesel (renewable derived from spent cooking oil) with Iraqi diesel. Iraqi diesel is known to be a high-sulfur fuel. Sulfur in diesel causes higher emissions of fine particles with hazardous properties. Therefore, adding biodiesel that does not contain sulfur will reduce the final sulfur content in the mixture and thus reduce the resulting soot. In the present study, the effect of added biodiesel when the engine is operating at a range of different loads up to the maximum level on the distribution of emitted particles is investigated. This study also aims to contribute outside the existing literature and compare the emission performance of a diesel engine using this bio-oxygenated fuel produced by a conventional alkaline catalyst. The main objectives of the work are: to operate the engine under different engine loading conditions and to compare multiple measurements of emitted nanoparticles with those emitted from Iraqi diesel combustion.

2. Methodology

In this study, refined edible oils and residual edible oils were used. In this work, refined cooking oil is treated with a stratification process to get rid of glycerin and impurities. To evaluate the pros and cons of biodiesel in a diesel engine, PM emitted from the engine exhaust of B20, B35 and B50 mixtures was measured. In the present investigation, the diesel engine used was a four-cylinder, four-stroke, water-cooled, naturally aspirated DI diesel engine. Experimental work was carried out on an open test bed. The research test bed is composed of diesel engine, dynamometer and other accessory parts. Parameters of engine were effectively measured for different load conditions from low to maximum engine load using biodiesel extracted from used cooking oils with diesel. In this study, the authors carried out experimental work to evaluate the particles present in the engine exhaust pipe.

2.1 Production and Properties of Biodiesel

The biodiesel used in this study was produced using the transesterification process (usually in the production of methyl esters). In this method, methanol is added to vegetable oil or fat using a catalyst of sodium hydroxide). This method produces methyl ester plus glycerol (with mixture no more than 20%). Previous study [48] explains the process mentioned in this section with details and description. Laboratory-produced biodiesel is added to fossil diesel fuel in portions and the resulting mixture is named according to the amount of biodiesel added. The mixture consisting of 20% biofuel + 80% diesel is called DB20 and so on for the rest of the mixtures. Table 1 shows some of the most important mixed media. The sulfur content of the diesel fuel used in the study was very high (12,340 ppm), and the laboratory-prepared biodiesel mixture had a low sulfur content with a percentage equal to the amount of biodiesel in the mixture.

Table 1
Properties of diesel fuel, biodiesel, and their mixtures

"Fuel type"	"Density" (kg/m^3)	"Viscosity" (cSt @ 40 °C)	"Heating value" (kJ/kg)	"Cloud point" (°C)	"Sulfur content"
"Diesel"	830	1.86	45,573	-41	12340
"DB20"	837	2.4	44,616	-31	9872
"DB35"	844.5	2.62	44,275	-22	8021
"DB50"	855.6	2.77	42,914	-19	6170
"B100"	881	4.2	40,296	-4	0

2.2 Experimental Setup

The engine used in this study is a Fiat diesel engine (TD 313 Diesel engine rig), the engine is water cooled, direct injection, natural aspirated one. The test engine is a European-made four-cylinder diesel engine and is equipped with a hydraulic dynamometer system to determine the load applied to the engine. This engine was selected because of its modular design and close resemblance to those used around the world. The maximum engine power is 60 kW, which is typical for some compact passenger cars. The engine is water-cooled, with a capacity of 3.66 litres and a compression ratio of 17:1. The engine is warmed up for 15 minutes before starting to measure the fuel mixture. To limit the test data, the first test phase was conducted at an average engine speed of 1,500 rpm (which represents the rotational speed of an urban engine at average speeds). The engine load was changed in steps, each equal to 10% of the total load of the maximum load. Engine load is adjusted using a hydraulic dynamometer. In the second part of the experiment, the engine rpm was changed by operating the engine load at a medium load. The measured speed indicates low, medium and high speeds. The engine is heated with diesel fuel and when the engine coolant temperature reaches to temperature of 90°C (which is the required), the engine switches to the type of mixture to be measured.

2.3 Analysis and Measurements of Emission

Five types of PM emissions are PM1, PM2.5, PM7, PM10, and TSP for five mixtures of diesel, DB20, DB35, DB50, B100, respectively. Emitted particle concentrations were measured using GT-521of Met One Model, which uses a laser photometer. The calibration of the device was approved by the Central Organization for Standardization and Quality Control in Baghdad, Iraq. A meter distance of the device from the exhaust outlet is placed to ensure emissions are reduced as required by the PM measurement conditions set by the manufacturer.

2.4. Uncertainty Analysis

Uncertainty analysis was utilized to perform a comprehensive evaluation of the statistical precision of the study and the empirical results. Through the application of this method, possible discrepancies observed in the calibration processes of instruments can be identified, thereby aiding in the prediction of data inaccuracies. The determination of uncertainty in the current research was based on the methodology proposed by Klein and McClintock. The following equation was employed to determine the various inaccuracies in experimental measurements:

$$W_R = [(\frac{\partial R}{\partial x_1} w_1)^2 + (\frac{\partial R}{\partial x_2} w_2)^2 + \cdots + (\frac{\partial R}{\partial x_n} w_n)^2]^{0.5}$$

W_R is a symbol denoting the overall uncertainty, with R representing the function of the independent variables (x_1, x_2, …, x_n) and (w_1, w_2, …, w_n) signifying the uncertainties of these independent variables. The uncertainty associated with the test reg can be found in Table 3. A total uncertainty of 2.83% was determined experimentally, indicative of a high level of accuracy and a low degree of uncertainty.

4. Results and Discussion

4.1 Engine Load Effect

Combustion is a very complex process and it is impossible to reduce the cause or effect of anything without dealing with its other effects. Two operating parameters were changing and studied in this study, such as speed and engine load, are measured for four types of emissions. PM emissions results are changing with varying engine load at constant speed as shown in Figure 1. Emission of PM1.0 is higher at both conditions (low and high loads) and it is lower at medium loads. Medium loads at medium speeds are used for testing and are good for mixing the fuel and allowing oxidation time. Using DB50 produced the lowest level of PM1.0 compared to the others. Reduction of PM1.0 compared to diesel: 4.2%, 14.2%, 24.78% and 34.63% for DB20, DB35, DB50 and B100. This study confirmed that reducing sulfur in oil has a significant impact on PM1.0 production.

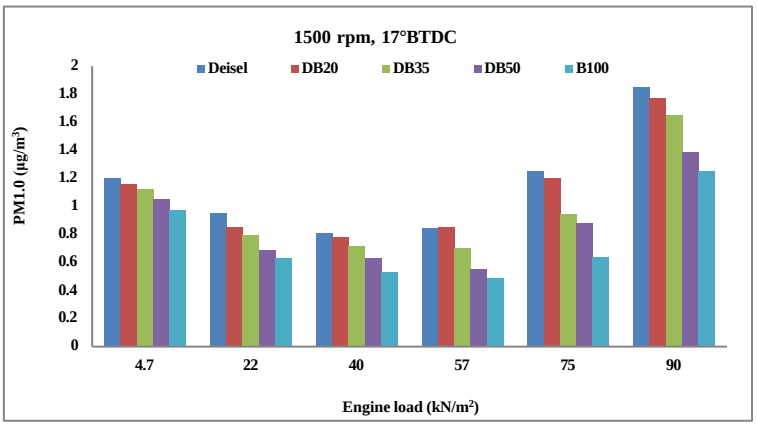


Fig. 1. Engine load effect on emitted PM1

The results in Figure 2 are approximately followed the same trend as Figure 1, with lower PM2.5 concentrations at medium loads and higher for both conditions of loads (low or high). The engine fed with biodiesel-diesel blends has given promoted results. Furthermore, the emissions of two types of PM (PM1.0 and PM2.5) in this study seem to be very small, counting the emissions of engines operating in many ways and shutting down these pollutants over days and weeks provides a real warning of the seriousness of these pollutants. The PM2.5 was reduced by 7.2%, 16.7%, 32.2% and 42.8% for DB20, DB35, DB50 and B100, respectively, compared to diesel.

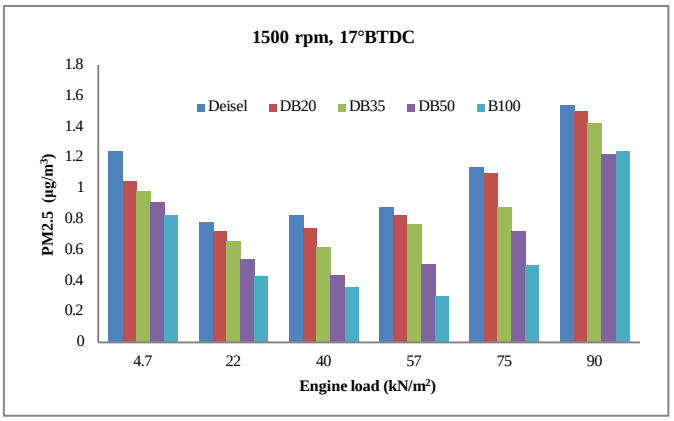


Fig. 2. Engine load effect on emitted PM2.5

Figure 3 presented the concentrations reduction of PM10 using biodiesel-diesel blends. The rates of reduction emitted the type levels of PM10 for DB20, DB35, DB50 and B100 in comparison with neat diesel were 12.93%, 21.11%, 31.64% and 42.73%, respectively.

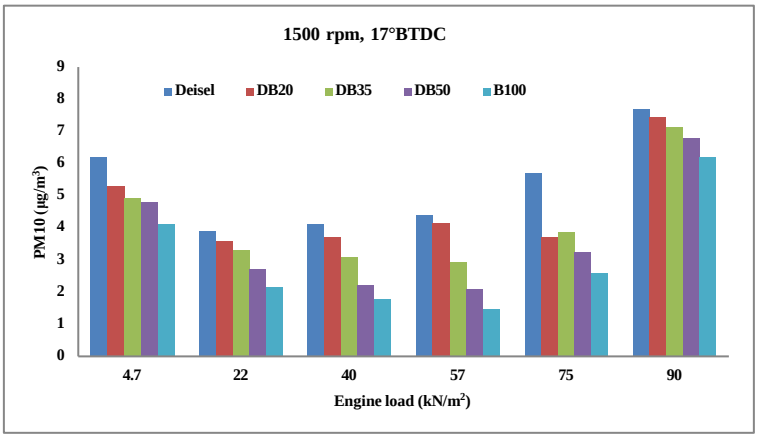


Fig. 3. Engine load effect on emitted PM10

Regarding the TSP released from the engine, the percentage reduction shown in Figure 4 is 4.98% for DB20, 12.07% for DB35, 21.54% for DB50 and 26.53% for B100 compared to diesel. The results showed that using biodiesel led to a reduction of particles in-cylinder in all directions, but the impact on nano- and PM was greater than the effect on particulate matter.

3.2 Engine Speed Effect

Figure 5 shows the effect of varying motor speed on PM1.0 molecules. PM1.0 is affected by engine speed because it is higher at lower speeds due to lower combustion chamber temperatures. In addition to the cold walls of the combustion chamber, this also increases pollution and prevents oxidation. PM1.0 has the lowest value at medium speed because there is enough time for the fuel to breathe and mix the fuel with air, there is enough heat in the combustion chamber to oxidize the fuel, and there is enough space for oxidation. PM1.0 concentration is increasing at a high rate. Although more heat is supplied to the combustion chamber, mixing time with the same oxide will decrease and molecular density will increase. Blending biodiesel into the diesel reduced the concentration of PM1.0 by 12.13% and 36.65% for DB20 and DB35, respectively, than to the diesel.

However, the combustion of DB50 and B100 decreased these pollutants by 60.92% and 81.06% compared to diesel. The findings in this study confirm the significant effect of sulfur content in used oils. Moreover, the presented of biodiesel decreased the sulfur content of the diesel and improved the oxygen content of the mixture, emissions from biodiesel-diesel blends were lower due to the lower sulfur content.

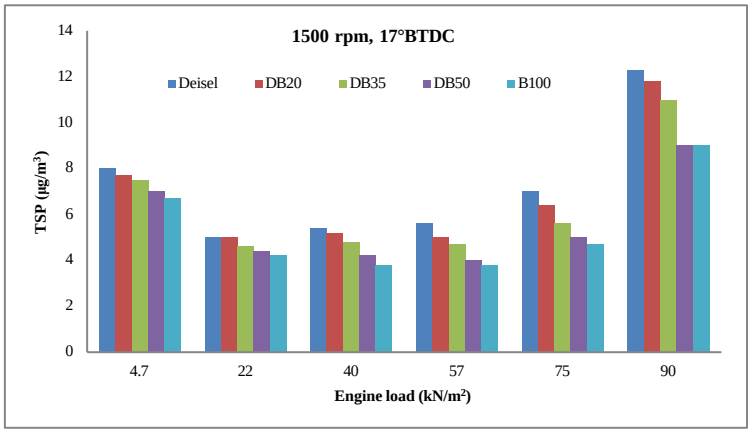


Fig. 4. Engine load effect on emitted TSP

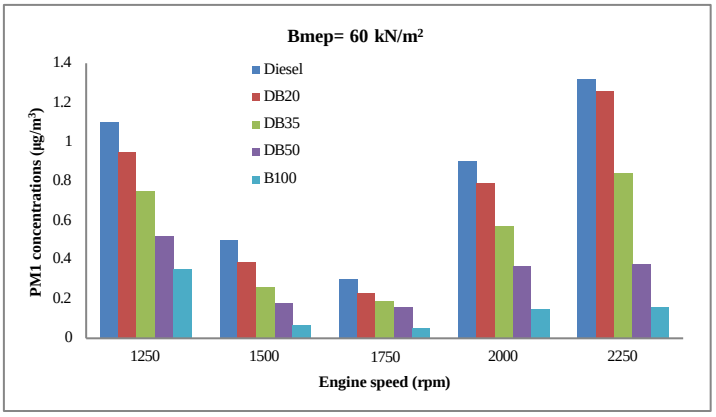


Fig. 5. Engine speed effect on emitted PM1

PM2.5 concentration in Figure 6 followed the results as PM1.0, decreasing at engine speeds with medium and increasing at low and engine speeds with high condition for the same reasons mentioned above (Figure 5). The addition of biodiesel resulted in a reduction of 21.29% and 25% for DB20 and DB35, respectively. However, when DB50 and B100 were used, the concentration decreased to 41.43% and 51.85%, respectively, compared to diesel. We believe that the decrease in the distribution of PM2.5 when adding biodiesel is not comparable to the case of PM1.0 due to the process of oxidation nearby and related molecules becomes difficult despite the oxygen effect that presented in the biodiesel.

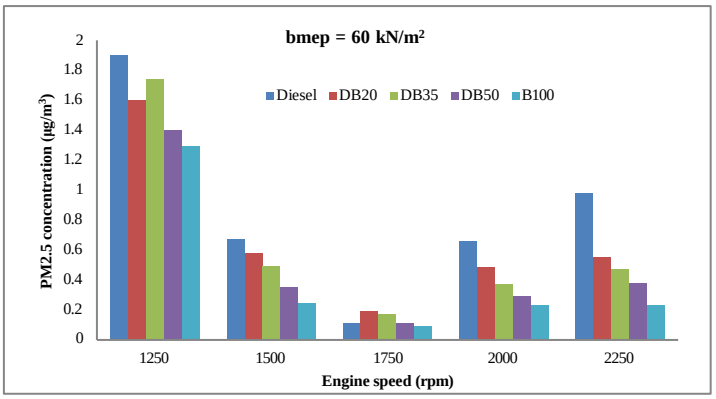


Fig. 6. Engine speed effect on emitted PM2.5

Figure 7 shows that the concentration of emitted PM10 is higher than that of other pollutants; This confirms that the larger the molecular size, the more difficult the oxidation process is. Biodiesel-diesel blends still offer a slight advantage over diesel; PM10 rates are 9%, 25.98%, 43% and 61.3% lower for DB20, DB35, DB50 and B100. Figures 5 to 7 show that the concentration of PM1.0 is increase more than PM2.5 and PM10 when presented B100, because the particulate matters are formed at the beginning as PM1.0 and then aggregated to form the rest of the particulate's sizes like both PM2.5 and PM10.

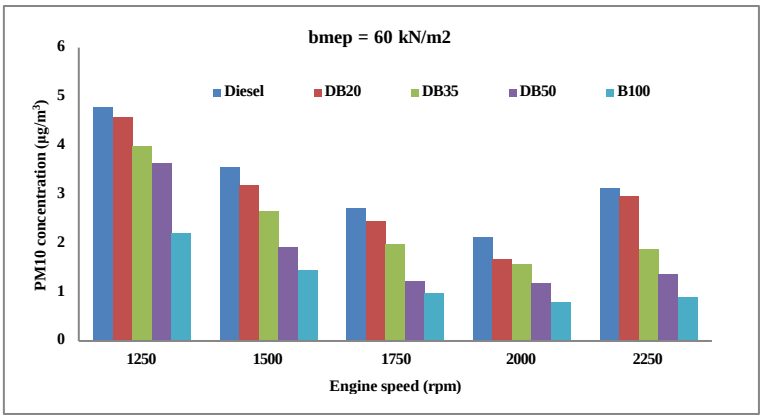


Fig. 7. Engine speed effect on emitted PM10

The effect of engine speed (Figure 8) on total suspensions particles (TSP) measured. The particles measured in device were mostly high and decreased at a moderate rate, and when biodiesel-diesel blends were used, the use of B100, DB50, DB35, DB20 lead to decrease of 51.9%, 35.2%, 19.6% and 9.37% compared to diesel. The above results confirm that reducing the sulfur content and increasing the oxygen content in fuel is very effective and significantly reduces total PM emissions.

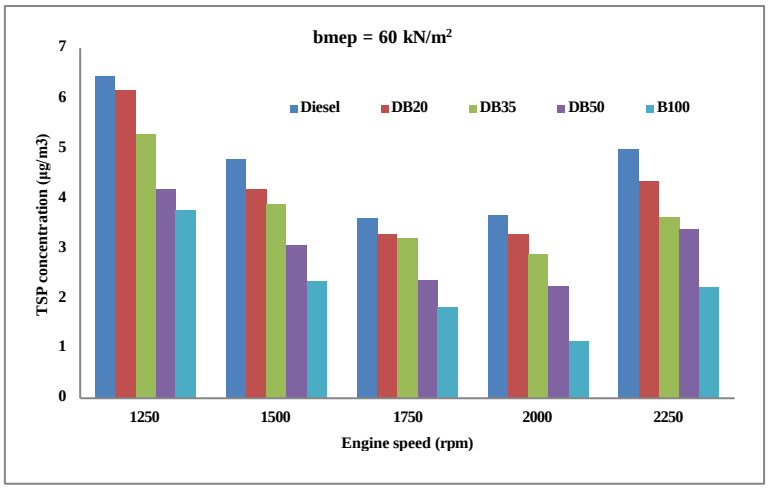


Fig. 8. Engine speed effect on emitted TSP

Figure 9 shows a comparison between some experimental studies that used biodiesel or mixtures of biodiesel and diesel or kerosene as fuel. The use of biodiesel with a high oxygen content reduces the emitted PM concentrations as is the case with the results of Refs. [50] and [52]. Ref. [48] introduced gaseous hydrogen with air and ignited it with biodiesel (pilot fuel) and the resulting PM concentrations were very low, reaching 3.8 µg/m^3. Ref 38 reduced PM concentrations by adding ethanol with a high oxygen and hydrogen content and recirculating the exhaust gas. Ref. [49] added biodiesel produced from waste restaurant oil (50%) to diesel with ultra-low sulfur content; the emitted PM was about 17 µg/m^3 at part load and speed of 1500 rpm. Refs. [3] and [51] added biodiesel to Iraqi kerosene, which has a much lower sulfur content than Iraqi diesel, so PM emissions reached 3.7 and 4 µg/m^3, respectively. In the present study, good mixing and use of suitable surfactant played an important role in achieving the lowest PM emissions, which was 3.07 µg/m^3.

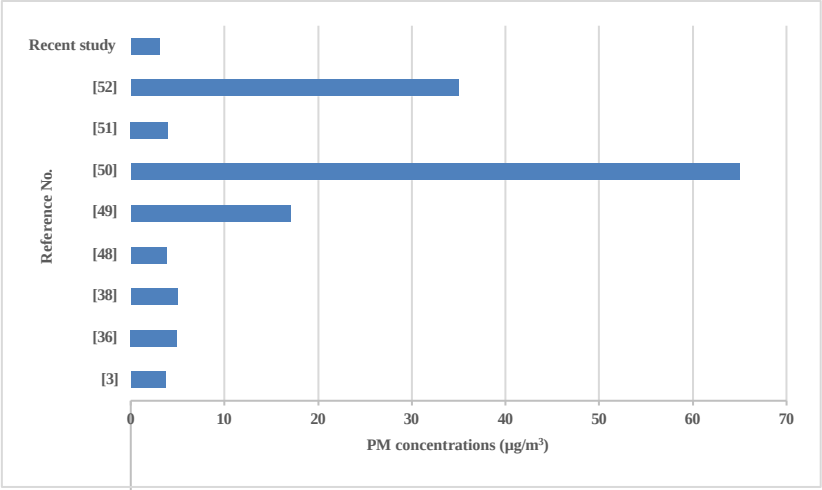


Fig. 9. Comparison between resulted PM concentrations for several studies from literature

4. Conclusion and Future Directions

The sulfur content of Iraqi diesel is high (between 10,000 and 25,000 ppm) and another alternative is used (especially in summer) to reduce the content: biodiesel. Biodiesel has no or very low sulfur content in its composition, making it the most acceptable additive to diesel fuel in Iraq,

which suffers from high and dangerous pollution levels. The results showed that the use of biodiesel-diesel blends reduced particulate emissions of all sizes and had a significant effect on the measured nanoparticles and fine particles.

1- Compared to diesel at constant load and variable engine speed, the significant reduction in PM1.0 was 81.06% for B100, while PM2.5 for DB20 decreased by 51.85%.
2- The use of biodiesel blends resulted in a significant reduction in particulate matter compared to diesel, where TSP was reduced by 51.9% when using DB50, while a good reduction was found in DB20 by 19.6%.
3- Most of the reductions in output units were at medium engine speeds and loads.
4- The variable PM measurements increased at both (low and high) engine speeds and loads.
5- There are two main reasons for the reduction in PM emissions in diesel and biodiesel blends: The high oxygen content in biodiesel leads to complete combustion and soot oxidation. The second reason is the presence of less sulfur in bio-oil.

The present study confirms that the emitted PM was significantly reduced using biodiesel and diesel blends. In addition to measuring different groups of emitted PM, this study indicates that PM needs further investigation due to its impact on the surrounding environment and human health. This research will allow for a better and easier understanding of the basic components and their differences within PM particles. Therefore, future work should investigate the chemical and physical effects of PM and how they affect PM formation and its impact on diesel engine performance and emissions in detail. Also, a clear revision for PM variable measures effects on human health should be conducted.

References

[1] Umar, Muhammad, Xiangfeng Ji, Dervis Kirikkaleli, and Andrew Adewale Alola. "The imperativeness of environmental quality in the United States transportation sector amidst biomass-fossil energy consumption and growth." *Journal of Cleaner Production* 285 (2021): 124863. https://doi.org/10.1016/j.jclepro.2020.124863

[2] Karin, Preechar, Aphichai Tripatara, Phyo Wai, Ban-Seok Oh, Chinda Charoenphonphanich, Nuwong Chollacoop, and Hidenori Kosaka. "Influence of ethanol-biodiesel blends on diesel engines combustion behavior and particulate matter physicochemical characteristics." *Case Studies in Chemical and Environmental Engineering* 6 (2022): 100249. https://doi.org/10.1016/j.cscee.2022.100249

[3] Hamza, Noor H., Noora S. Ekaab, and Miqdam T. Chaichan. "Impact of using Iraqi biofuel–kerosene blends on coarse and fine particulate matter emitted from compression ignition engines." *Alexandria Engineering Journal* 59, no. 3 (2020): 1717-1724. https://doi.org/10.1016/j.aej.2020.04.031

[4] Zhang, Yanhui, Yunhao Zhong, Jie Wang, Dongli Tan, Zhiqing Zhang, and Dayong Yang. "Effects of different biodiesel-diesel blend fuel on combustion and emission characteristics of a diesel engine." *Processes* 9, no. 11 (2021): 1984. https://doi.org/10.3390/pr9111984

[5] Kumar, Sanjesh, and Geetesh Goga. "Emission characteristics & performance analysis of a diesel engine fuelled with various alternative fuels–a review." *Materials Today: Proceedings* (2023). https://doi.org/10.1016/j.matpr.2023.02.457

[6] Rajak, Upendra, Ümit Ağbulut, Abhishek Dasore, and Tikendra Nath Verma. "Artificial intelligence based-prediction of energy efficiency and tailpipe emissions of soybean methyl ester fuelled CI engine under variable compression ratios." *Energy* 294 (2024): 130861. https://doi.org/10.1016/j.energy.2024.130861

[7] Singh, Mandeep, and Sarbjot Singh Sandhu. "Performance, emission and combustion characteristics of multi-cylinder CRDI engine fueled with argemone biodiesel/diesel blends." *Fuel* 265 (2020): 117024. https://doi.org/10.1016/j.fuel.2020.117024

[8] Sharma, Abhinav, Prem Kumar, Sarbjot Singh Sandhu, and Mandeep Singh. "Experimental investigation into the effects of Argemone biodiesel/diesel blends on cyclic variations in a multi-cylinder CRDI engine." *Clean Energy* 7, no. 2 (2023): 363-374. https://doi.org/10.1093/ce/zkac081

[9] Chaichan, Miqdam T. "Combustion and emission characteristics of E85 and diesel blend in conventional diesel engine operating in PPCI mode." *Thermal science and Engineering progress* 7 (2018): 45-53. https://doi.org/10.1016/j.tsep.2018.04.013

[10] Das, A., Gajghate, S.S., Das, S. and Ghatak, M.D., 2024. An Experimental Investigation on Performances and Emission Characteristics in a Multi-Cylinder Diesel Engine Using Nahar Oil Biodiesel Blended With Carbon Nano Tube. *Heat Transfer Engineering*, pp.1-12. https://doi.org/10.1080/01457632.2024.2317606

[11] Gopal, Rajendiran, K. Mayilsamy, R. Subramanian, R. Venkatachalam, and N. Nedunchezhian. "Comparative study on multi-cylinder DI diesel engine using hybrid fuel blends (diesel-biodiesel-ethanol derivative) as fuel." *International Journal of Oil, Gas and Coal Technology* 33, no. 1 (2023): 55-74. https://doi.org/10.1504/IJOGCT.2023.130374

[12] Zhang, Yanhui, Yunhao Zhong, Shengsen Lu, Zhiqing Zhang, and Dongli Tan. "A comprehensive review of the properties, performance, combustion, and emissions of the diesel engine fueled with different generations of biodiesel." *Processes* 10, no. 6 (2022): 1178. https://doi.org/10.3390/pr10061178

[13] Mubarak, M., A. Shaija, and T. V. Suchithra. "Experimental evaluation of Salvinia molesta oil biodiesel/diesel blends fuel on combustion, performance and emission analysis of diesel engine." *Fuel* 287 (2021): 119526. https://doi.org/10.1016/j.fuel.2020.119526

[14] Dubey, Ashish, Ravi Shankar Prasad, Jitendra Kumar Singh, and Ashish Nayyar. "Optimization of diesel engine performance and emissions with biodiesel-diesel blends and EGR using response surface methodology (RSM)." *Cleaner Engineering and Technology* 8 (2022): 100509. https://doi.org/10.1016/j.clet.2022.100509

[15] Geng, Limin, Leichao Bi, Qi Li, Hao Chen, and Yuantao Xie. "Experimental study on spray characteristics, combustion stability, and emission performance of a CRDI diesel engine operated with biodiesel–ethanol blends." *Energy Reports* 7 (2021): 904-915. https://doi.org/10.1016/j.egyr.2021.01.043

[16] Dhahad, Hayder A., Mohammed A. Fayad, Miqdam T. Chaichan, Alaa Abdulhady Jaber, and T. Megaritis. "Influence of fuel injection timing strategies on performance, combustion, emissions and particulate matter characteristics fueled with rapeseed methyl ester in modern diesel engine." *Fuel* 306 (2021): 121589. https://doi.org/10.1016/j.fuel.2021.121589

[17] Yang, Hao, Yongqiang Zhang, Cong Li, Yu Fang, and Xinghu Li. "Physicochemical characteristics of particulate matter emitted from the oxygenated fuel/diesel blend engine." *Aerosol and Air Quality Research* 21, no. 12 (2021): 210175. https://doi.org/10.4209/aaqr.210175

[18] Zhu, Yiyi, and Hongqin Fan. "Use of biodiesel in non-road mobile machineries for low-carbon construction: policy review and lifecycle analysis." *Journal of Cleaner Production* 421 (2023): 138543. https://doi.org/10.1016/j.jclepro.2023.138543

[19] Dahham, Rami Y., Haiqiao Wei, and Jiaying Pan. "Improving thermal efficiency of internal combustion engines: recent progress and remaining challenges." *Energies* 15, no. 17 (2022): 6222. https://doi.org/10.3390/en15176222

[20] McCarrick, Sarah, Mathilde N. Delaval, Ulrike M. Dauter, Annette M. Krais, Anastasiia Snigireva, Asmamaw Abera, Karin Broberg, Axel C. Eriksson, Christina Isaxon, and Anda R. Gliga. "Toxicity of particles derived from combustion of Ethiopian traditional biomass fuels in human bronchial and macrophage-like cells." *Archives of Toxicology* 98, no. 5 (2024): 1515-1532. https://doi.org/10.1007/s00204-024-03692-8

[21] Hassan, Muhammad Azher, Tariq Mehmood, Junjie Liu, Xiaosan Luo, Xinghua Li, Mohsin Tanveer, Muhammad Faheem, Awais Shakoor, Afzal Ahmed Dar, and Muhammad Abid. "A review of particulate pollution over Himalaya region: Characteristics and salient factors contributing ambient PM pollution." *Atmospheric Environment* 294 (2023): 119472. https://doi.org/10.1016/j.atmosenv.2022.119472

[22] Engels, Sean M., Pratik Kamat, G. Stavros Pafilis, Yukang Li, Anshika Agrawal, Daniel J. Haller, Jude M. Phillip, and Lydia M. Contreras. "Particulate matter composition drives differential molecular and morphological responses in lung epithelial cells." *PNAS nexus* 3, no. 1 (2024): pgad415. https://doi.org/10.1093/pnasnexus/pgad415

[23] Yang, Ning, Xiaowen Deng, Bin Liu, Liwei Li, Yuan Li, Peng Li, Miao Tang, and Lin Wu. "Combustion performance and emission characteristics of marine engine burning with different biodiesel." *Energies* 15, no. 14 (2022): 5177. https://doi.org/10.3390/en15145177

[24] Simsek, Suleyman, Samet Uslu, and Hatice Simsek. "Proportional impact prediction model of animal waste fat-derived biodiesel by ANN and RSM technique for diesel engine." *Energy* 239 (2022): 122389. https://doi.org/10.1016/j.energy.2021.122389

[25] Jayaseelan, G. Antony Casmir, A. Anderson, Murali Krishnan Poduva, and P. V. Sudheesh. "Synthesis and performances characteristics of biodiesel from animal fat." *Materials Today: Proceedings* 45 (2021): 6053-6056. https://doi.org/10.1016/j.matpr.2020.10.002

[26] Srinivasan, G.R., Shankar, V., Chandra Sekharan, S., Munir, M., Balakrishnan, D., Mohanam, A. and Jambulingam, R., 2020. Influence of fatty acid composition on process optimization and characteristics assessment of biodiesel

produced from waste animal fat. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp.1-19. https://doi.org/10.1080/15567036.2020.1771477

[27] Fayad, Mohammed A., Miqdam T. Chaichan, Hayder A. Dhahad, Ahmed A. Al-Amiery, and Wan Nor Roslam Wan Isahak. "Reducing the effect of high sulfur content in diesel fuel on NO x emissions and PM characteristics using a PPCI mode engine and gasoline–diesel blends." *ACS omega* 7, no. 42 (2022): 37328-37339. https://doi.org/10.1021/acsomega.2c03878

[28] Kurczyński, Dariusz, Grzegorz Wcisło, and Piotr Łagowski. "Experimental study of fuel consumption and exhaust gas composition of a diesel engine powered by biodiesel from waste of animal origin." *Energies* 14, no. 12 (2021): 3472. https://doi.org/10.3390/en14123472

[29] Simsek, Suleyman, and Samet Uslu. "Comparative evaluation of the influence of waste vegetable oil and waste animal oil-based biodiesel on diesel engine performance and emissions." *Fuel* 280 (2020): 118613. https://doi.org/10.1016/j.fuel.2020.118613

[30] Palani, Yogesh, Chandramohan Devarajan, Dhanashekar Manickam, and Sathish Thanikodi. "Performance and emission characteristics of biodiesel-blend in diesel engine: A review." *Environmental Engineering Research* 27, no. 1 (2022). https://doi.org/10.4491/eer.2020.338

[31] Sun, Ying, Lin Lyu, and Miaomiao Wen. "Experimental study on reducing BC emissions from a low-speed marine engine by using blended biodiesel and a nitro additive." *Process Safety and Environmental Protection* 185 (2024): 1232-1249. https://doi.org/10.1016/j.psep.2024.03.086

[32] Yusuf, Abdulfatah Abdu, Danjuma Abdu Yusuf, Zhu Jie, Tajuddeen Yusuf Bello, Magaji Tambaya, Bala Abdullahi, Ibrahim Ali Muhammed-Dabo, Ibrahim Yahuza, and H. Dandakouta. "Influence of waste oil-biodiesel on toxic pollutants from marine engine coupled with emission reduction measures at various loads." *Atmospheric Pollution Research* 13, no. 1 (2022): 101258. https://doi.org/10.1016/j.apr.2021.101258

[33] Fayad, Mohammed A., Amera A. Radhi, Salman Hussien Omran, and Farag Mahel Mohammed. "Influence of environment-friendly fuel additives and fuel injection pressure on soot nanoparticles characteristics and engine performance, and NOX emissions in CI diesel engine." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 88, no. 1 (2021): 58-70. https://doi.org/10.37934/arfmts.88.1.5870

[34] Visan, Nicolae Adrian, Razvan Carlanescu, Dan Catalin Niculescu, and Radu Chiriac. "Study on the cumulative effects of using a high-efficiency turbocharger and biodiesel B20 fuelling on performance and emissions of a large marine diesel engine." *Journal of Marine Science and Engineering* 10, no. 10 (2022): 1403. https://doi.org/10.3390/jmse10101403

[35] Fayad, Mohammed A., Slafa I. Ibrahim, Salman H. Omran, Francisco J. Martos, Tawfik Badawy, Ayad M. Al Jubori, Hayder A. Dhahad, and Miqdam T. Chaichan. "Experimental effect of CuO2 nanoparticles into the RME and EGR rates on NOX and morphological characteristics of soot nanoparticles." *Fuel* 331 (2023): 125549. https://doi.org/10.1016/j.fuel.2022.125549

[36] Fayad, Mohammed A., Miqdam T. Chaichan, and Hayder A. Dhahad. "Engine performance and PM concentrations from the combustion of Iraqi sunflower oil biodiesel under variable diesel engine operating conditions." In *Journal of Physics: Conference Series*, vol. 1973, no. 1, p. 012051. IOP Publishing, 2021. https://doi.org/10.1088/1742-6596/1973/1/012051

[37] Lawan, Ibrahim, Weiming Zhou, Zaharaddeen Nasiru Garba, Mingxin Zhang, Zhanhui Yuan, and Lihui Chen. "Critical insights into the effects of bio-based additives on biodiesels properties." *Renewable and sustainable energy reviews* 102 (2019): 83-95. https://doi.org/10.1016/j.rser.2018.12.008

[38] Chaichan, Miqdam T., Noora S. Ekab, Mohammed A. Fayad, and Hayder A. Dhahad. "PM and NOX emissions amelioration from the combustion of diesel/ethanol-methanol blends applying exhaust gas recirculation (EGR)." In *IOP Conference Series: Earth and Environmental Science*, vol. 961, no. 1, p. 012044. IOP Publishing, 2022. https://doi.org/10.1088/1755-1315/961/1/012044

[39] Al-Kheraif, Abdulaziz A., Asad Syed, Abdallah M. Elgorban, Darshan Devang Divakar, Rajasree Shanmuganathan, and Kathirvel Brindhadevi. "Experimental assessment of performance, combustion and emission characteristics of diesel engine fuelled by combined non-edible blends with nanoparticles." *Fuel* 295 (2021): 120590. https://doi.org/10.1016/j.fuel.2021.120590

[40] Attia, Ali MA, A. R. Kulchitskiy, Mohamed Nour, Ahmed I. El-Seesy, and Sameh A. Nada. "The influence of castor biodiesel blending ratio on engine performance including the determined diesel particulate matters composition." *Energy* 239 (2022): 121951. https://doi.org/10.1016/j.energy.2021.121951

[41] Tiwari, Kamta Prasad, and Ram Narayan Singh. "Review on Performance and Emissions Characteristics of Compression Ignition Engine Fueling Non-Edible Vegetable Oil." *Applied Mechanics and Materials* 919 (2024): 107-122. https://doi.org/10.4028/p-CyKiD1

[42] Venkatesan, V., N. Nallusamy, and P. Nagapandiselvi. "Waste-to-energy approach for utilizing non-edible soapnut oil methyl ester as a fuel in a twin-cylinder agricultural tractor diesel engine." *Energy & Fuels* 34, no. 2 (2020): 1958-1964. https://doi.org/10.1021/acs.energyfuels.9b04184

[43] Prabhu, C., B. Navaneetha Krishnan, T. Prakash, V. Rajasekar, Dhinesh Balasubramanian, Van Vang Le, Nguyen Viet Linh Le, Phuoc Quy Phong Nguyen, and Van Nhanh Nguyen. "RETRACTED: Biodiesel unsaturation and the synergic effects of hydrogen sharing rate on the characteristics of a compression ignition engine in dual-fuel mode." (2023): 126699. https://doi.org/10.1016/j.fuel.2022.126699

[44] Barik, Debabrata, Bhaskor Jyoti Bora, Prabhakar Sharma, Bhaskar Jyoti Medhi, Dhinesh Balasubramanian, R. L. Krupakaran, Ravikumar Ramegowda et al. "Exploration of the dual fuel combustion mode on a direct injection diesel engine powered with hydrogen as gaseous fuel in port injection and diesel-diethyl ether blend as liquid fuel." *International Journal of Hydrogen Energy* 52 (2024): 827-840. https://doi.org/10.1016/j.ijhydene.2023.06.083

[45] Makhonko, N. I., Yu A. Plotnikova, E. A. Tarasova, N. L. Varshamova, and E. V. Yashina. "Environmental problems of biofuel production in modern energy." In *IOP Conference Series: Earth and Environmental Science*, vol. 688, no. 1, p. 012005. IOP Publishing, 2021. https://doi.org/10.1088/1755-1315/688/1/012005

[46] Pramanik, Atreyi, Aashna Sinha, Kundan Kumar Chaubey, Sujata Hariharan, Deen Dayal, Rakesh Kumar Bachheti, Archana Bachheti, and Anuj K. Chandel. "Second-generation bio-fuels: Strategies for employing degraded land for climate change mitigation meeting United Nation-sustainable development goals." *Sustainability* 15, no. 9 (2023): 7578. https://doi.org/10.3390/su15097578

[47] CHAICHAN, MIQDAM T., NOORA S. EKAB, and ISAM E. YOUSIF. "Experimental evaluation of the combustion and emission characteristics of waste non-edible restaurant oils and high-sulfur diesel." *J Eng Sci Technol* 18, no. February (2023): 307-322.

[48] Chaichan, Miqdam Tariq. "Performance and emission characteristics of CIE using hydrogen, biodiesel, and massive EGR." *International Journal of Hydrogen Energy* 43, no. 10 (2018): 5415-5435. https://doi.org/10.1016/j.ijhydene.2017.09.072

[49] Wei, Long, Chun Shun Cheung, and Zhi Ning. "Influence of waste cooking oil biodiesel on combustion, unregulated gaseous emissions and particulate emissions of a direct-injection diesel engine." *Energy* 127 (2017): 175-185. https://doi.org/10.1016/j.energy.2017.03.117

[50] Ali, Mohd Affandi Mohd, Jolius Gimbun, Kun Lu Lau, Chin Kui Cheng, Dai-Viet N. Vo, Su Shiung Lam, and Rosli Mohd Yunus. "Biodiesel synthesized from waste cooking oil in a continuous microwave assisted reactor reduced PM and NOx emissions." *Environmental research* 185 (2020): 109452. https://doi.org/10.1016/j.envres.2020.109452

[51] Ekaab, Noora Salih, Noor Hussein Hamza, and Miqdam T. Chaichan. "Performance and emitted pollutants assessment of diesel engine fuelled with biokerosene." *Case Studies in Thermal Engineering* 13 (2019): 100381. https://doi.org/10.1016/j.csite.2018.100381

[52] Cheung, Chun Shun, X. J. Man, K. W. Fong, and O. K. Tsang. "Effect of waste cooking oil biodiesel on the emissions of a diesel engine." *Energy Procedia* 66 (2015): 93-96. https://doi.org/10.1016/j.egypro.2015.02.050