Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Influence of Sophisticated Post-Injection Strategy and Oxygenated Fuel Blends on PM Characteristics and Improvement in Soot Oxidation Reactivity in Diesel Engine

Mohammed Ali Fayad[1,*], Azher Mouhsen Abed[2], Hussain Ali Hussain[3], Asifa Mohammed[4], Shaimaa Bassim Al-Baghdadi[1], Raghad Rahman Mahdi[1], Salman Hussien Omran[1], Tawfik Badawy[5]

[1] Energy and Renewable Energies Technology Center, University of Technology- Iraq, Baghdad, Iraq
[2] Air Conditioning and Refrigeration Techniques Engineering Department, College of Engineering and Technologies, Al-Mustaqbal University, 51001 Hilla, Babylon, Iraq
[3] Advance Welding Solutions Company Ltd, Baghdad, Iraq
[4] Department of Electromechanical Engineering, University of Technology- Iraq, Baghdad, Iraq
[5] Mechanical Power Engineering Department, Cairo University, Egypt

ARTICLE INFO

Article history:
Received 13 August 2024
Received in revised form 1 December 2024
Accepted 10 December 2024
Available online 20 December 2024

Keywords:
Post-injection; oxygenated fuel; NOX emissions; soot; oxidation

ABSTRACT

Multiple injections strategy have been commonly effective technique applied in engines to reduce the exhaust emissions and management of exhaust catalyst systems. The effect of post-injection strategy (PIS) on soot characteristics and emissions in compression ignition (CI) diesel engine operating with oxygenated fuels (B100, B20 and B16) was experimentally studied in this study. In addition, the effect of PIS and oxygenated fuels properties on emissions, oxidation reactivity and nanostructure of soot emissions are studied and analysed. It is indicated that the PIS increase the emissions of CO and THC, while the NO_X emissions slightly decreased for all fuels. Furthermore, the NO_X emissions decreased by 12.6% from the effects of PIS and oxygenated fuels in comparison with diesel. The oxygenated fuels enhance the oxidation reactivity of soot emission to be faster than to the diesel. The nanostructure of soot formation generated from oxygenated fuel showed disorder shape in graphen layers of soot emissions in comparison with diesel. Furthermore, the internal structure of soot emission indicated that more space between graphen layers and hollow in case of oxygenated fuels which result in easier oxidation compared to the diesel. For all fuels, B16 presented attractive results in reduction NO_X and soot characteristics for both size and nanostructure compared to the other fuels.

1. Introduction

The critical emissions of particulate matter (PM) and nitrogen oxides (NO_X) are consider a major concerning in diesel engines over recent investigation on engine emissions. Different technologies of common-rail (CR), exhaust gas recirculation (EGR), and injection strategies are contribute in

* *Corresponding author.*
E-mail address: mohammed.a.fayad@uotechnology.edu.iq

https://doi.org/10.37934/arfmts.125.2.93105

significant emissions reduction and beneficial to meet the stringent regulations of emission [1,2]. Recently, post-injection strategy (PIS) play a vital role in decline PM and in the same time enhance the exhaust temperature as mentioned in the literature [3,4]. Yoon *et al.,* [5] stated that the late post-injection (70 °CAD) after top dead centre (aTDC) can be improve both systems efficiency of diesel for particulate filter (PF) and oxidation catalyst (OC). The trend of smoke opacity and soot in the exhaust pipe of DI diesel engine is examined by Hotta *et al.,* [6] for different PI timing. The study obtained that the smoke reduction can be achieved when presents early PI timing after top dead centre (aTDC). Previous study by Hardy and Reitz [7] indicated that the combustion efficiency and PM enhanced from apply PIS. Previous work by Chen [8] reported that the soot emissions can be reduced by 42% through presented PIS with no penalty in NOX emissions. Park and Bae [9] found that the emissions of CO and THCs reduced when using PIS in diesel engine. In contrast, other works by Fayad *et al.,* [10] and Yamamoto *et al.,* [11] documented that the PIS increases the hydrocarbons emissions from the combustion of biodiesel and diesel in CR engine. Further, the PIS impact on hydrocarbon speciation and soot emissions from diesel fuel combustion was analysed by Storey *et al.,* [12] under different operating conditions of engine. They found that the late PIS timing enhance the formation of light hydrocarbons, while no sensitive noticed with heavy hydrocarbons. Another work by Jeftić and Zheng [13] studied the effect of post-injection on gaseous emission composition and exhaust gas temperature in diesel engine from combustion of n-butanol blend and diesel fuel. The outcome from this study showed that the THC and CO are significantly reduced with early PI. Besides, late PIS is one of the additional approach to increasing the temperature in the exhaust pipe of modern diesel engines. Moreover, late PIS is good way to the re-catalyst which can generating high level of THC emissions and this approved by previous work of Fayad *et al.,* [10].

Biodiesel and bioalcohol are receiving more attention in last years ago due to meet the requirement of stringent emission legislation. Many benefits can be founded from the attractive properties of biodiesel such as easily available, technically feasible and environmentally acceptable [14]. The edible or non-edible feedstock of biodiesel used in internal combustion (IC) engines as good alternative conventional diesel fuel [15,16]. It is reported that the promising alternative source to replace conventional fuels is biodiesel produced from microalgae [17]. However, previous experimental works stated that the alcohol-diesel blend can improve exhaust temperature and emissions with respect to diesel fuels [10,18]. Besides, the unburnt THC, soot emissions and CO reduces from the burning of the alcohol molecules [19]. For these benefits, alcohol blends are offering more focus as better fuel than to diesel fuel. It is documented in the literature that the CO emission and soot particle reduced when using the butanol-diesel blends compared to the conventional diesel fuel.

Pollutants emissions emitted from the diesel fuel combustion leads to serious problems linked with environment and health issues [20]. It is reported in the literature that the first generation of biodiesel can provide lesser level of HC, CO and PM than to the diesel [19,21]. In the same work, it was also found that the polycyclic aromatic hydrocarbon (PAH) and soot emissions reduced from biodiesel combustion with respect to the diesel fuel. Same findings reduction of engine emissions was informed from the alcohol-diesel combustion [22,23]. The average soot particles number and emissions of carbonaceous decreased when the engine fuelling with B20 [3,24]. In contrast, Lin amd Lin [25] stated that the 10% reduction of NO_X emissions obtained when using neat biodiesel [26]. Biodiesel burning produced high combustion temperature as observed in most of the literature studies which leads to the increases the NO_X emissions [27,28]. Syahmi *et al.,* [29] studied the effect of blended 7 % and 30% Euro 5 diesel-biodiesel blend on engine performance and exhaust emissions. They found that the lowers CO and CO2 emissions, and increases NOx emissions, while lowers brake power and increases BSFC. In case of alcohol blends, it was no clear agreement about increase or decrease NO_X emissions [30,31]. Injected fuel late in the combustion cycle can help in decline the PM and NO_X emissions. It is documented in many works that the PIS gives better particulate reduction and boost the systems performance of diesel catalyst [32,33]. Also the PIS assists decrease the particulate formation and enrich soot oxidation within delay combustion cycle. The oxidation rate of soot characteristics was investigated by Yehliu *et al.,* [34], they found that the soot particles increases with late PIS. In addition, soot emissions decreased by around 30% with PIS without penalty in NO_X emissions [35]. The interaction between oxygenated fuels and PIS are important to meet the regulations of stringent emission. Recent studies reported that the literature are focused on the effect of biodiesel and PIS on the emission levels in the exhaust tailpipe [10,22]. It is stated in different studies on effect of PIS, but still unclear how the exhaust emissions and soot particles can be affected by PIS. Furthermore, the effect of PIS on PM and NO_X emissions were studied in the literatures for diesel and biodiesel and total concentration of PM. Therefore, the main objective of this study is investigate the impacts of PIS and oxygenated fuel blends on exhaust gas emissions and PM charactrestics. Furthermore, study the effect of post-injection strategy (PIS) on particulate characteristics of number and concentration as well as oxidation activity of soot particles. The soot nanostructure of were also highlighted in this study from oxygenated fuel combustion.

2. Research Methodology

2.1 Materials and Equipment

In this study, the oxygenated fuels biodiesel and butanol were mixed in different percentages with conventional diesel fuel. Proportion 20% biodiesel (Sunflowers oil) was mixed with 80% diesel to prepare B20 blend, while 16% alcohol and 15% biodiesel (Sunflowers oil) were mixed with 69% diesel to prepare B16 blend. The blending technique and preparation method of oxygenated fuel blends used in this study was mentioned in the previous study [19]. For the same oxygen content, the effect of physicochemical properties of oxygenated fuels blends on NO_X and PM emissions characteristics was highlighted. General Company of Vegetable Oils is provided biodiesel that derived from the Sunflowers oil. Properties of diesel (D), biodiesel (B), and their blends (B20 and B16) are shown in Table 1. Before starting each test, the oxygenated blends were prepared in the time of test to enhance the fresh fuel properties and to get homogenous blends.

Table 1
Specifications of tested fuels

Properties	Diesel	Biodiesel	B20	B16
Chemical formula	$C_{16}H_{34}$	$C_{19}H_{36}O_2$		$C_{11}H_{21.4}O_{0.5}$
Derived cetane number	51.8	62	53.4	
Latent heat of vaporization (kJ/kg)	242	216	-	
bulk modulus (MPa)	1410	1554	-	
density at 15 °C (kg/m^3)	844.3	896.1	860.6	836.5
Calorific value (MJ/kg)	45.80	38.90	53.41	39.68
Falsh & Fire point (°C)	65-70	157-162	81-86	94-97
Water content by coulometric KF (mg/kg)	40	170	389.4	378.6
kinematic viscosity at 40 °C (cSt)	2.77	5.0	3.224	2.64
Stoichiometric air fuel ratio	14.4	-	-	-
lubricity at 60 °C(µm)	312	205	404.5	406.2

The exhaust emissions emitted from engine were measured at the engine outlet (CO, NO_X, and HC) using type Multigas mode 4880 of exhaust gas analyser. To avoid the condensation of THC between the analysing unit and the sampling unit, the sampling lines were heated to reach 190 °C.

After each test, the sampling lines were purged to eliminate the sampling lines from any fuel condensation. The concentration levels of emissions were recorded for both conditions (beginning and end of test). Thermogravimetric analysis (TGA) was used to analyse the oxidation reactivity of soot particles. The equipments of scaning mobility particle sizer (SMPS) and transmission electron microscopy (TEM) type Philips CM-200 with an accelerating voltage of 200 kV and resolution about 2 Å were used to record the PM concentrations and evaluation the soot particle morphology characteristics, respectively. The soot image obtained by TEM is analysed using digital image analysis Matlab software to calculate the characteristicsof soot nanoparticles, which in turn to analyses the physical properties of soot particulate [36,37].

2.2 Engine Setup and Test Conditions

In this study, a modern 4-cylinder, CR diesel engine and tools was conducted as presented in Figure 1. The FIS was controlled during the test by using CR fuel injection system. The range of engine speed is from 1000 to 2000 rpm with 17:1 compression ratio. Further, the minimum and maximum value of fuel injection pressure is between 500 to 1500 bar, respectively, while the maximum value of indicated mean effective pressure (IMEP) is 7 bar. Thermocouple (E-type) was used to record the temperature of exhaust pipe as well as to check that the engine was fully warm. In addition, the temperature of water and fuel were measured using thermocouples (T-type). Before real test, the engine was operated at least 30 min with diesel fuel to reach the steady-state condition and to warm the engine and get the necessary temperature for test, and then performed for other fuel types.

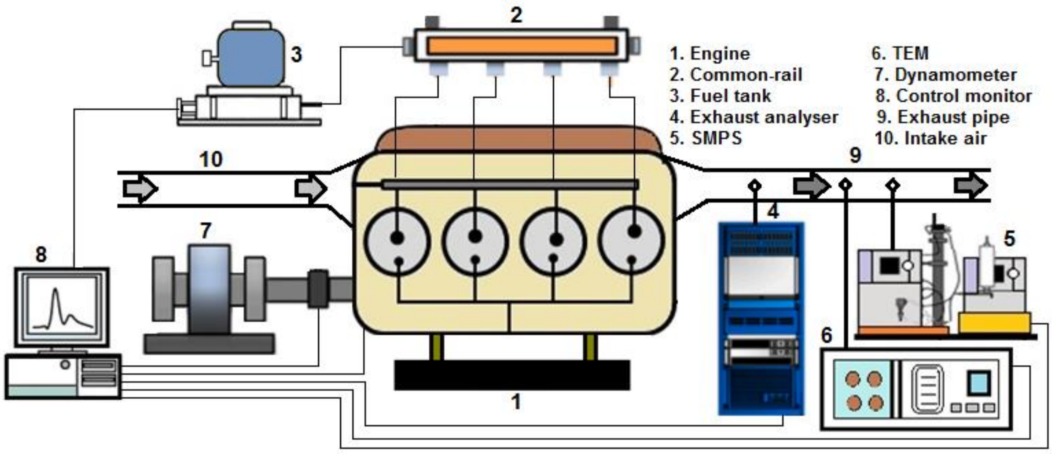

Fig. 1. Schematic of engine operation setup and tools

At 1500 rpm, the engine speed was fixed for all the tests, while IMEP and fuel injection pressure were kept at 4 bar and 550 bar, respectively. During all engine tests, PIS was carried out at 45° CAD aTDC. For experiments, diesel fuel feed the engine to start the test, while the new fuel was conducted in the engine and operated for 20 min to clean out the fuel pipeline from the remaining previous fuel. To record basic data for comparison, diesel fuel was the first test performed. Three test measurements were repeated for each condition, the results were averaged to get good results and to prevent an error could be occurred within experiments.

3. Results and Discussion

3.1 Emission Characteristics

Figure 2 compares the results of exhaust emissions from the oxygenated blends and diesel under PIS. For all fuels, this figure, B16 emitted lower engine-out emissions of THC and CO in comparison with other fuels tested. More reasons could be help in reduction the engine-out emissions from B16 such as complete combustion, better mixing, vaporisation, active oxygen content and atomization. The high level of THC is significantly owing to incomplete combustion and poor mixing process of air-fuel [38]. In contrast, diesel fuel burning showed highest emissions production than to the oxygenated fuel due to high aromatic carbon and high sulfur content in the fuel properties [39]. The emissions of CO and THC tend to increase with PIS, while NO_X emissions decline by 12.6% from oxygenated fuel in comparison with diesel, for the same condition of PIS. It is thought that the part of fuel is sucked under PIS into the combustion process which result in deteriorate the fuel combustion and produces high level of THC in the exhaust part. An incomplete combustion of hydrocarbon-based fuel leads to produce the CO emission that formed in low-temperature combustion environment or in the lean oxygen. Figure 2 revealed that PIS leads to increase the in-cylinder temperature which results in inhibit the formation of NO_X emissions. It is reported in the previous study that NO_X emissions decreased when PIS is greater than 80 °CA [40]. It is stated that oxygen enrichment and high combustion temperature are the main roles to promote the NO_X formation. The findings from the current study are compatible with prior study which reported that NO_X emissions reduced with increase the fuel amount of the PIS (from 20 °CA to 80 °CA) [41]. Furthermore, the increasing quantity of PIS from 5 mg to 10 mg leads to decrease the NO_X emissions from 7.8% to 26.9%, respectively, as mentioned in the previous studies [13,42]. It can be noticed that the hydrocarbon free radical increased from the effect of PIS which help in decreasing the NO_X emissions level. It is stated that PIS of fuel can cracking to produce hydrocarbon free radicals to form nitro HCs after react with emissions of NO_X, which in turn decreasing the NO_X emissions concentration [11].

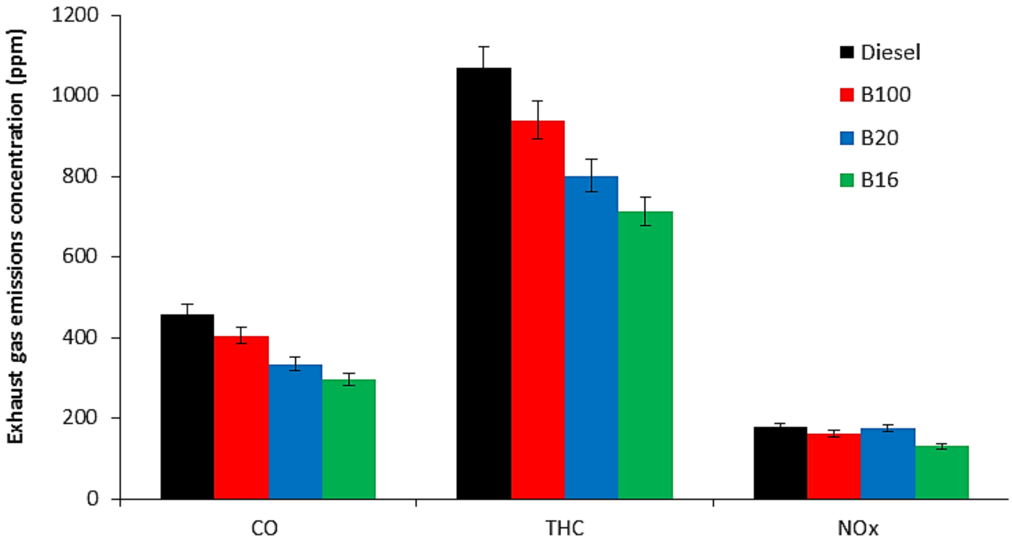

Fig. 2. Exhaust gas emissions analysis for B100, B20, B16 and diesel

3.2 PM Size Distribution

PM concentrations from the PIS effect and oxygenated fuels (B100, B20 and B16) are analysed and compared with diesel fuel as shown in Figure 3. For the same PIS, it is clear that oxygenated fuels produced lower PM than those high PM concentrations from diesel. The high PM oxidation inside cylinder and along exhaust pipe due to oxygen-bond from the oxygenated blends could be help in PM reduction [43]. Furthermore, B16 appear good reduction in the PM concentrations when compared with B100, B20 and diesel (Figure 3). These results are consistent with the finding made by other previous studies [44,45]. Under PIS condition, the generation of PM inhibited due to increase the temperature of the combustion in late cycle of combustion which result in enhance the oxidation of PM. It is reported that the late PIS at 40 °CA leads to decreased the soot emissions for diesel fuel when compared with single condition of injection [41]. Previous studies stated that PIS enhance the oxidation rate of soot emissions due to the combustion exotherm and the additional turbulent energy provided by PIS [46,47].

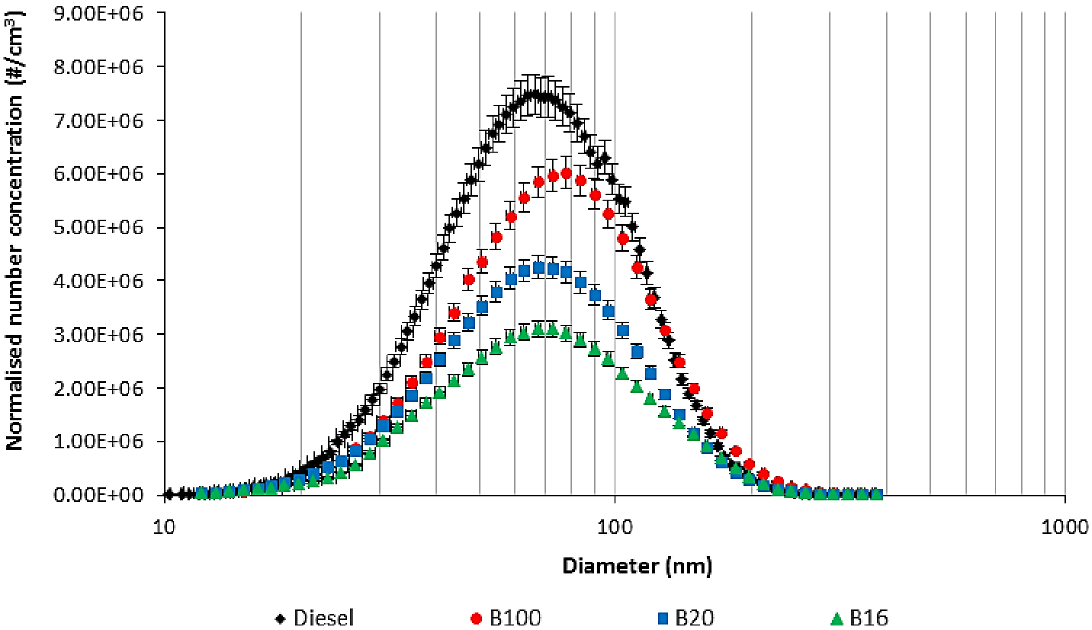

Fig. 3. PM concentration and number for B100, B20, B16 and diesel

3.3 Oxidation Reactivity

The generated soot samples from the combustion of oxygenated and diesel were analysed in this study. Figure 4 and Figure 5 show the soot mass loss and weight losses from the oxidation reactivity of soot emissions emitted from B16, B20, B100 and diesel under PIS. It is clear from Figure 4 that the soot particles losses mass from the oxygen-bond fuels faster than to the base fuel. The soot characteristics and soot oxidative reactivity affected by compounds contained in oxygenated fuels which enhance the rate of soot oxidation and reactivity [48]. Furthermore, the fuel-bound oxygen has significant impact on the oxidation and reactivity of soot emissions. Similar results reported in the study by Song *et al.,* [49] that the combustion of biodiesel, B20% biodiesel and Fischer-Tropsch synthetic diesel fuel improved the reactivity of soot derived from these fuels compared to the diesel. Figure 5 shows that the oxygenated fuels oxidise early at low temperatures in comparison with diesel. Thus indicated that the high combustion temperature from the oxygenated fuel and PIS have positive effect on the oxidation rate and help the soot emissions oxidise at lower temperature [10,50]. The high reactivity of soot emissions from oxygenated fuels was explained by authors that the soot undergoes to internal burning which in turn completely destruction the formation eventual structures of graphene layer and the core [51]. B16 shows better mass losses and high oxidation reactivity of soot emissions due to active oxygen content which contributing in decrease the total soot inside combustion cycle and along the exhaust pipe.

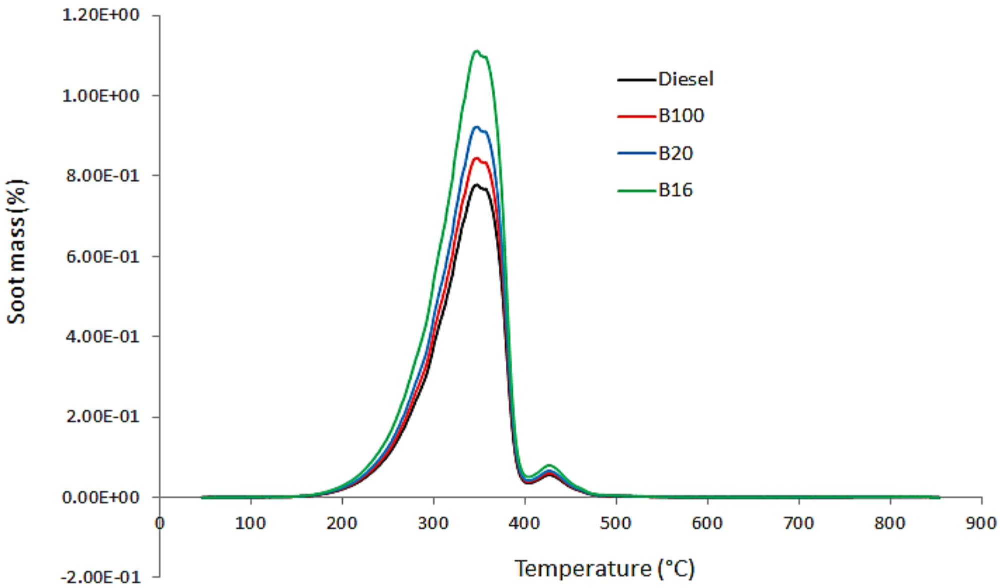

Fig. 4. TGA analysis of soot oxidation for B100, B20, B16 and diesel

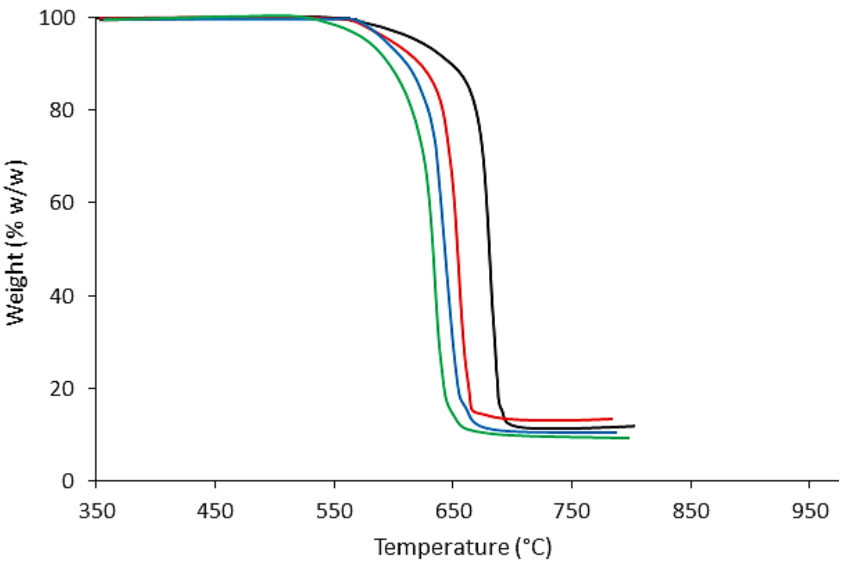

Fig. 5. TGA analysis of soot emission for B100, B20, B16 and diesel

3.4 Soot Nanoparticles Structure

The oxygenated fuels incorporated with PIS shows different size and nanostructure of soot emissions as shown in Figure 6 and Figure 7, respectively. According to the TEM images, it is clear that the oxygenated fuels produces smaller size of soot particles than those emitted from regular diesel (Figure 6). The high soot particles formed from diesel combustion and high collisions between these emission contributing in increase the number and size of soot compared to oxygenated fuels combustion. The internal and external nanostructure of soot particles generated from the

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
Volume 125, Issue 2 (2025) 93-105

oxygenated fuels combustion shows disorder graphen layers and hollow inside soot structure compared to the diesel fuel (Figure 7). The molecular structure of oxygen atom in the oxygenated fuels could be helped in destruction the internal structure of soot emission and interaction the graphen layers to be in disorder form, thereby these results support the above results obtained by TGA. These results of nanostructure are agreement with nanostructure analysis in previous study [19]. In comparison of oxygenated fuels, the active oxygen-fuel bond in B16 and delay PIS has more effect on soot suppression and plays a key role in changing the structure of soot emission compared to the B100 and B20 as shown in Figure 7. The large space between graphen layers and high temperature inside the soot structure produced from oxygenated fuels could be beneficial for the soot oxidation at short time and lower temperature in comparison with diesel. Also, the results of nanostructure confirm the lower number of soot emission (Figure 6) emitted from the oxygenated fuels. The increase temperature in the late cycle from PIS also helps to increase the oxidation rate for the soot that already formed. The internal structure of soot and its primary particles have been studied by Boehman *et al.,* [52]. They found that the origin and type of fuel properties effect on the reactivity and changing nanostructure of soot characteristics. It is thought that the surface oxygen content on external graphen layers of soot produced from oxygenated fuels could be also provide easier penetration inside soot and destroy the internal structure of soot emission. Another reason is the higher reactivity and lower structural ordered of soot generated from oxygenated fuels help in exhibited the small size and high space between graphen layers with non-uniform layers of soot as depicted in Figure 7.

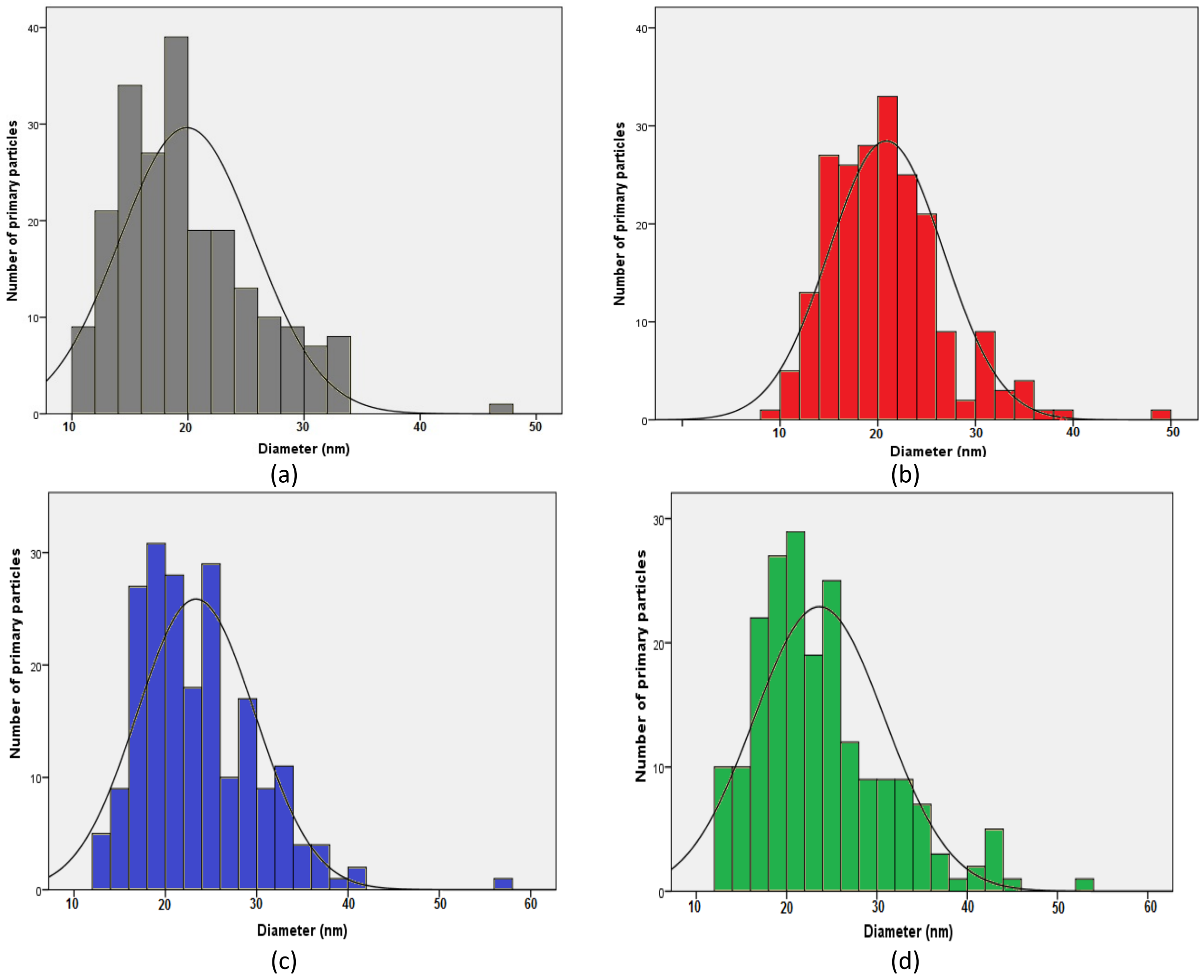

Fig. 6. Number of soot particles for (a) diesel, (b) B100, (c) B20, and (d) B16

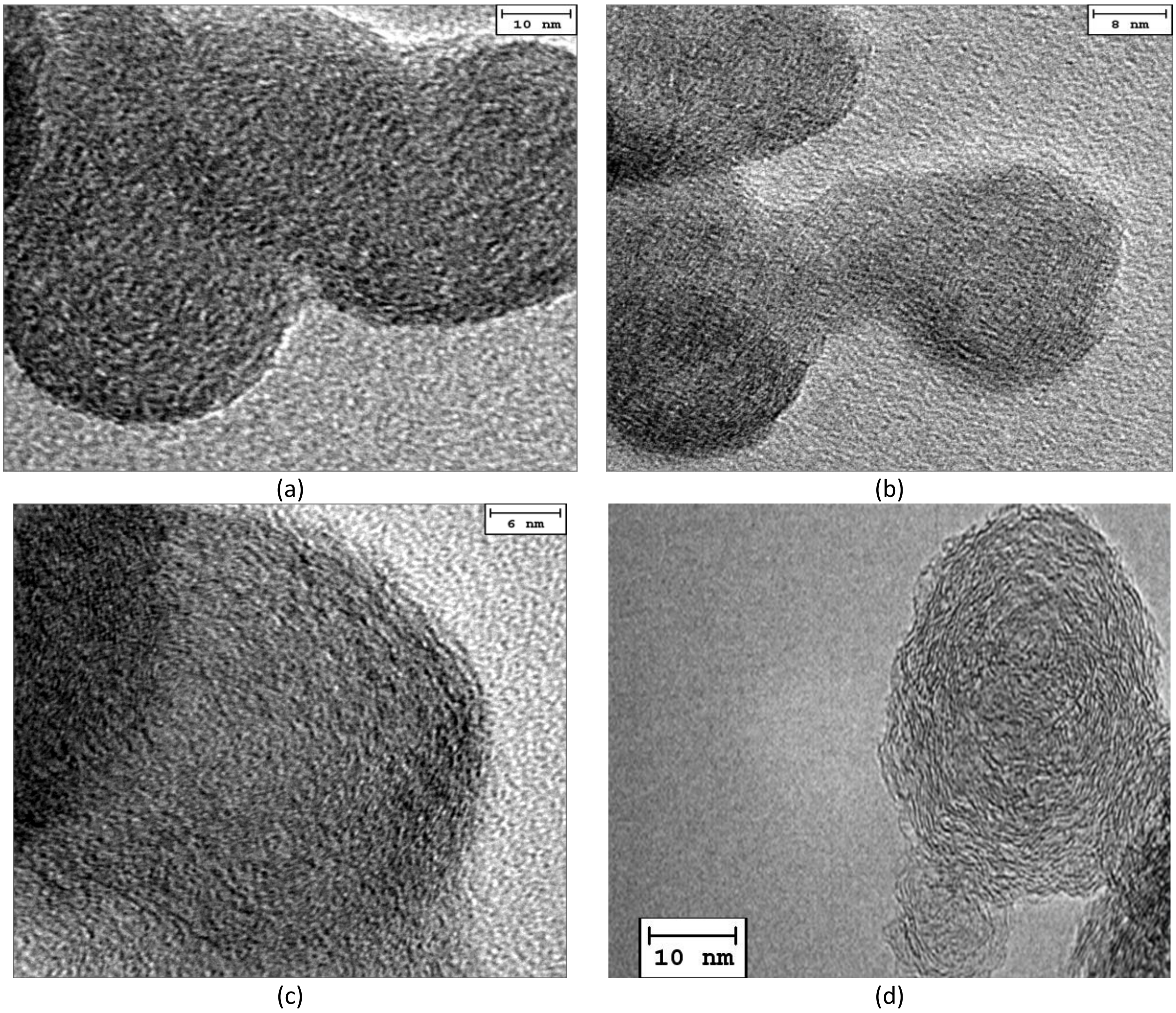

Fig. 7. High-resolution of TEM images for (a) diesel, (b) B100, (c) B20, and (d) B16

4. Conclusions

The impacts of oxygenated fuels (B100, B20, B16 and diesel) and PIS on emission and characteristics of soot oxidation reactivity and soot nanostructure in CR diesel engine were examined in this study. However, the tendencies of soot to the oxidative reactivity and soot nanostructure from the combustion of oxygenated fuels and diesel are summarized into the following conclusions:

i. It was observed that PIS operation had beneficial for NO_X emissions reduction by 12.6% from oxygenated fuel compared to the diesel. PIS led to increase the THC and CO emissions for all fuels, while NO_X emissions slightly decrease with PIS.
ii. The particles concentration of PM declined from oxygenated fuels, especially in B16, it was found that the PM reduction more than other fuels.
iii. This study gives insight and further understanding on the soot form and the condition of their production from the combustion of oxygenated fuels and diesel under PIS.
iv. Smaller size and lower number of soot emission produced from combustion of oxygenated fuels and applied post-injection strategy.
v. Oxygenated fuels showed high oxidative reactivity of soot emission at lower temperatures in comparison with diesel.

vi. The soot generated from oxygenated fuels exhibited less ordered and more space between graphen layers in internal strcture of soot emission compared to the diesel.
vii. It was observed that easier oxidation of soot particles from oxygenated fuels due to more hollow inside soot and oxygen content on the surface of soot which allows to easier oxidation of soot particles.

It is recommended that the additional work on the effect of fuel injection pressures and oxygenated fuel with exhaust gas recirculation (EGR) on soot reactivity and formation will be highlighted in the future study.

Conflict of interests
The authors confirm and declare that there is no conflict of interests regarding the publication of this paper.

References
[1] Kumar, M. Vijay, A. Veeresh Babu, and P. Ravi Kumar. "The impacts on combustion, performance and emissions of biodiesel by using additives in direct injection diesel engine." *Alexandria Engineering Journal* 57, no. 1 (2018): 509-516. https://doi.org/10.1016/j.aej.2016.12.016
[2] Yao, Mingfa, Hu Wang, Zunqing Zheng, and Yan Yue. "Experimental study of n-butanol additive and multi-injection on HD diesel engine performance and emissions." *Fuel* 89, no. 9 (2010): 2191-2201. https://doi.org/10.1016/j.fuel.2010.04.008
[3] Fayad, M. A., David Fernandez-Rodriguez, J. M. Herreros, M. Lapuerta, and Athanasios Tsolakis. "Interactions between aftertreatment systems architecture and combustion of oxygenated fuels for improved low temperature catalysts activity." *Fuel* 229 (2018): 189-197. https://doi.org/10.1016/j.fuel.2018.05.002
[4] Fayad, Mohammed A., Bashar R. AL-Ogaidi, Marwa K. Abood, and Hind A. AL-Salihi. "Influence of post-injection strategies and CeO_2 nanoparticles additives in the C30D blends and diesel on engine performance, NOX emissions, and PM characteristics in diesel engine." *Particulate Science and Technology* 40, no. 7 (2022): 824-837. https://doi.org/10.1080/02726351.2021.2017088
[5] Yoon, Sungjun, Hongsuk Kim, Daesik Kim, and Sungwook Park. "Effect of fuel injection strategy on DPF regeneration in single cylinder diesel engine." In *Internal Combustion Engine Division Fall Technical Conference*, vol. 57281, p. V002T04A010. American Society of Mechanical Engineers, 2015. https://doi.org/10.1115/ICEF2015-1140
[6] Hotta, Yoshihiro, Minaji Inayoshi, Kiyomi Nakakita, Kiyoshi Fujiwara, and Ichiro Sakata. *Achieving lower exhaust emissions and better performance in an HSDI diesel engine with multiple injection*. No. 2005-01-0928. SAE Technical Paper, 2005. https://doi.org/10.4271/2005-01-0928
[7] Hardy, W. L., and Rolf D. Reitz. *An Experimental Investigation of Partially Premixed Combustion Strategies Using Multiple Injections in a Heavy-Duty Diesel Engine*. No. 2006-01-0917. SAE Technical Paper, 2006. https://doi.org/10.4271/2006-01-0917
[8] Chen, S. Kevin. *Simultaneous Reduction of NOx and Particulate Emissions by Using Multiple Injections in a Small Diesel Engine*. No. 2000-01-3084. SAE Technical Paper, 2000. https://doi.org/10.4271/2000-01-3084
[9] Park, Youngsoo, and Choongsik Bae. *Effects of single and double post injections on diesel PCCI combustion*. No. 2013-01-0010. SAE Technical Paper, 2013. https://doi.org/10.4271/2013-01-0010
[10] Fayad, M. A., Athanasios Tsolakis, D. Fernández-Rodríguez, J. Martin Herreros, F. J. Martos, and M. Lapuerta. "Manipulating modern diesel engine particulate emission characteristics through butanol fuel blending and fuel injection strategies for efficient diesel oxidation catalysts." *Applied Energy* 190 (2017): 490-500. https://doi.org/10.1016/j.apenergy.2016.12.102
[11] Yamamoto, Kanta, Keishi Takada, Jin Kusaka, Yasuharu Kanno, and Makoto Nagata. *Influence of diesel post injection timing on HC emissions and catalytic oxidation performance*. No. 2006-01-3442. SAE Technical Paper, 2006. https://doi.org/10.4271/2006-01-3442
[12] Storey, John M., Samuel A. Lewis, Brian H. West, Shean P. Huff, C. Scott Sluder, Robert M. Wagner, Norberto Domingo, John Thomas, and Michael Kass. "Hydrocarbon species in the exhaust of diesel engines equipped with advanced emissions control devices." *Coordinating Research Council, Inc. CRC Project No. AVFL-10b-2* (2005).
[13] Jeftić, Marko, and Ming Zheng. "A study of the effect of post injection on combustion and emissions with premixing enhanced fueling strategies." *Applied Energy* 157 (2015): 861-870. https://doi.org/10.1016/j.apenergy.2015.02.052

[14] 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
[15] Jain, Siddharth, and M. P. Sharma. "Stability of biodiesel and its blends: a review." *Renewable and Sustainable Energy Reviews* 14, no. 2 (2010): 667-678. https://doi.org/10.1016/j.rser.2009.10.011
[16] Fayad, M. A., A. M. Abed, S. H. Omran, A. A. Jaber, A. A. Radhi, H. A. Dhahad, M. T. Chaichan, and T. Yusaf. "Influence of Renewable Fuels and Nanoparticles Additives on Engine Performance and Soot Nanoparticles Characteristics." *International Journal of Renewable Energy Development* 11, no. 4 (2022): 1068-1077. https://doi.org/10.14710/ijred.2022.45294
[17] Kong, Yu Man, Joon Hin Lee, Kiat Moon Lee, and Wah Yen Tey. "Techniques of improving microalgae in biomass clean energy: A short review." *Progress in Energy and Environment* 10 (2019): 6-20.
[18] Valentino, Gerardo, Stefano Iannuzzi, and Felice Esposito Corcione. *Experimental investigation on the combustion and emissions of a light duty diesel engine fuelled with butanol-diesel blend*. No. 2013-01-0915. SAE Technical Paper, 2013. https://doi.org/10.4271/2013-01-0915
[19] Fayad, Mohammed A., Jose M. Herreros, Francisco J. Martos, and Athanasios Tsolakis. "Role of alternative fuels on particulate matter (PM) characteristics and influence of the diesel oxidation catalyst." *Environmental Science & Technology* 49, no. 19 (2015): 11967-11973. https://doi.org/10.1021/acs.est.5b02447
[20] Alani, W. K., J. Zheng, M. A. Fayad, and Lei Lei. "Enhancing the fuel saving and emissions reduction of light-duty vehicle by a new design of air conditioning worked by solar energy." *Case Studies in Thermal Engineering* 30 (2022): 101798. https://doi.org/10.1016/j.csite.2022.101798
[21] Yesilyurt, Murat Kadir. "The evaluation of a direct injection diesel engine operating with waste cooking oil biodiesel in point of the environmental and enviroeconomic aspects." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 40, no. 6 (2018): 654-661. https://doi.org/10.1080/15567036.2018.1454546
[22] Fayad, Mohammed A. "Effect of renewable fuel and injection strategies on combustion characteristics and gaseous emissions in diesel engines." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 42, no. 4 (2020): 460-470. https://doi.org/10.1080/15567036.2019.1587091
[23] Emiroğlu, A. Osman, and Mehmet Şen. "Combustion, performance and emission characteristics of various alcohol blends in a single cylinder diesel engine." *Fuel* 212 (2018): 34-40. https://doi.org/10.1016/j.fuel.2017.10.016
[24] Zhang, Zhi-Hui, and Rajasekhar Balasubramanian. "Investigation of particulate emission characteristics of a diesel engine fueled with higher alcohols/biodiesel blends." *Applied Energy* 163 (2016): 71-80. https://doi.org/10.1016/j.apenergy.2015.10.173
[25] Lin, Cherng-Yuan, and Hsiu-An Lin. "Engine performance and emission characteristics of a three-phase emulsion of biodiesel produced by peroxidation." *Fuel Processing Technology* 88, no. 1 (2007): 35-41. https://doi.org/10.1016/j.fuproc.2006.07.008
[26] Bugosh, Gregory S., Rachel L. Muncrief, and Michael P. Harold. "Emission analysis of alternative diesel fuels using a compression ignition benchtop engine generator." *Energy & Fuels* 25, no. 10 (2011): 4704-4712. https://doi.org/10.1021/ef2009452
[27] Robbins, Curtis, S. Kent Hoekman, Eric Ceniceros, and Mani Natarajan. *Effects of biodiesel fuels upon criteria emissions*. No. 2011-01-1943. SAE Technical Paper, 2011. https://doi.org/10.4271/2011-01-1943
[28] Fayad, Mohammed A. "Investigation the impact of injection timing and pressure on emissions characteristics and smoke/soot emissions in diesel engine fuelling with soybean fuel." *Journal of Engineering Research* 9, no. 2 (2021). https://doi.org/10.36909/jer.v9i2.9683
[29] Syahmi, Anwar, Mas Fawzi, Shahrul Azmir Osman, and Harrison Lau. "Engine Performance and Exhaust Emission Effect of Increasing Euro5 Diesel Fuel Blended with 7% to 30% Palm Biodiesel." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 28, no. 2 (2022): 34-40. https://doi.org/10.37934/araset.28.2.3440
[30] How, Heoy Geok, Haji Hassan Masjuki, Md Abul Kalam, and Yew Heng Teoh. "Influence of injection timing and split injection strategies on performance, emissions, and combustion characteristics of diesel engine fueled with biodiesel blended fuels." *Fuel* 213 (2018): 106-114. https://doi.org/10.1016/j.fuel.2017.10.102
[31] Fayad, M. A., A. Tsolakis, F. J. Martos, M. Bogarra, I. Lefort, and K. D. Dearn. "Investigation the effect of fuel injection strategies on combustion and morphology characteristics of PM in modern diesel engine operated with oxygenate fuel blending." *Thermal Science and Engineering Progress* 35 (2022): 101476. https://doi.org/10.1016/j.tsep.2022.101476
[32] Caliskan, Hakan, and Kazutoshi Mori. "Environmental, enviroeconomic and enhanced thermodynamic analyses of a diesel engine with diesel oxidation catalyst (DOC) and diesel particulate filter (DPF) after treatment systems." *Energy* 128 (2017): 128-144. https://doi.org/10.1016/j.energy.2017.04.014

[33] 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 NOx 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

[34] Yehliu, Kuen, Octavio Armas, Randy L. Vander Wal, and André L. Boehman. "Impact of engine operating modes and combustion phasing on the reactivity of diesel soot." *Combustion and Flame* 160, no. 3 (2013): 682-691. https://doi.org/10.1016/j.combustflame.2012.11.003

[35] Benajes, Jesús, Santiago Molina, and José M. García. *Influence of Pre-and Post-Injection on the Performance and Pollutant Emissions in a HD Diesel Engine*. No. 2001-01-0526. SAE Technical Paper, 2001. https://doi.org/10.4271/2001-01-0526

[36] Lapuerta, Magín, Rosario Ballesteros, and Francisco J. Martos. "A method to determine the fractal dimension of diesel soot agglomerates." *Journal of Colloid and Interface Science* 303, no. 1 (2006): 149-158. https://doi.org/10.1016/j.jcis.2006.07.066

[37] Fayad, Mohammed A., Athanasios Tsolakis, and Francisco J. Martos. "Influence of alternative fuels on combustion and characteristics of particulate matter morphology in a compression ignition diesel engine." *Renewable Energy* 149 (2020): 962-969. https://doi.org/10.1016/j.renene.2019.10.079

[38] Tan, Yong Ren, Qiren Zhu, Yichen Zong, Jiawei Lai, Maurin Salamanca, Jethro Akroyd, Wenming Yang, and Markus Kraft. "The influence of alcohol, carbonate and polyethers as oxygenated fuels on the soot characteristics from a CI engine." *Fuel* 338 (2023): 127296. https://doi.org/10.1016/j.fuel.2022.127296

[39] 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 CuO_2 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

[40] Fayad, Mohammed A., Hind A. Al-Salihi, Hayder A. Dhahad, Farag M. Mohammed, and Bashar R. Al-Ogidi. "Effect of post-injection and alternative fuels on combustion, emissions and soot nanoparticles characteristics in a common-rail direct injection diesel engine." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* (2021): 1-15. https://doi.org/10.1080/15567036.2021.1970292

[41] Wu, Yan, Pan Wang, Sheikh Muhammad Farhan, Jing Yi, and Lili Lei. "Effect of post-injection on combustion and exhaust emissions in DI diesel engine." *Fuel* 258 (2019): 116131. https://doi.org/10.1016/j.fuel.2019.116131

[42] Zheng, Zunqing, Lang Yue, Haifeng Liu, Yuxuan Zhu, Xiaofan Zhong, and Mingfa Yao. "Effect of two-stage injection on combustion and emissions under high EGR rate on a diesel engine by fueling blends of diesel/gasoline, diesel/n-butanol, diesel/gasoline/n-butanol and pure diesel." *Energy Conversion and Management* 90 (2015): 1-11. https://doi.org/10.1016/j.enconman.2014.11.011

[43] Yage, Di, Zhang Junjie, Cheung Chun Shun, Miao Xuelong, Zheng Jinbao, Peng Haiyong, and Wu Tao. "Comparative study on combustion and particulate emissions for diesel-biodiesel and diesel-diglyme blends." *Fuel* 313 (2022): 122710. https://doi.org/10.1016/j.fuel.2021.122710

[44] Fayad, Mohammed A., Mohammed Sobhi, Miqdam T. Chaichan, Tawfik Badawy, Wisam Essmat Abdul-Lateef, Hayder A. Dhahad, Talal Yusaf, Wan Nor Roslam Wan Isahak, Mohd S. Takriff, and Ahmed A. Al-Amiery. "Reducing soot nanoparticles and NOX emissions in CRDI diesel engine by incorporating TiO_2 nano-additives into biodiesel blends and using high rate of EGR." *Energies* 16, no. 9 (2023): 3921. https://doi.org/10.3390/en16093921

[45] Zhao, Zichuan, Shuai Liu, Zhong Wang, Xinchang Zhu, Libin Zhang, and Qixai Zhang. "Effect of ash in biodiesel combustion particulate matter on the oxidation characteristics of carbon soot." *Journal of the Energy Institute* 105 (2022): 262-272. https://doi.org/10.1016/j.joei.2022.08.008

[46] Arrègle, Jean, José V. Pastor, J. Javier López, and Antonio García. "Insights on postinjection-associated soot emissions in direct injection diesel engines." *Combustion and Flame* 154, no. 3 (2008): 448-461. https://doi.org/10.1016/j.combustflame.2008.04.021

[47] Beatrice, C., P. Belardini, C. Bertoli, N. Del Giacomo, and Ma Migliaccio. *Downsizing of common rail DI engines: Influence of different injection strategies on combustion evolution*. No. 2003-01-1784. SAE Technical Paper, 2003. https://doi.org/10.4271/2003-01-1784

[48] Fayad, Mohammed Ali, Asifa Mohammed, Raghad Rahman Mahdi, Hussain Ali Hussain, Salman Hussien Omran, and Azher Mouhsen Abed. "The Impact of Incorporating EGR Rates and Coconut Biodiesel on Morphological Characteristics of Particulate Matter in a Compression Ignition Diesel Engine." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 119, no. 1 (2024): 134-145. https://doi.org/10.37934/arfmts.119.1.134145

[49] Song, Juhun, Mahabubul Alam, André L. Boehman, and Unjeong Kim. "Examination of the oxidation behavior of biodiesel soot." *Combustion and Flame* 146, no. 4 (2006): 589-604. https://doi.org/10.1016/j.combustflame.2006.06.010

[50] Lee, Kyeong Ook, Roger Cole, Raj Sekar, Mun Young Choi, Jinyu Zhu, Jinsuk Kang, and Choongsik Bae. *Detailed characterization of morphology and dimensions of diesel particulates via thermophoretic sampling*. No. 2001-01-3572. SAE Technical Paper, 2001. https://doi.org/10.4271/2001-01-3572

[51] Song, Juhun, Mahabubul Alam, and André L. Boehman. "Impact of alternative fuels on soot properties and DPF regeneration." *Combustion Science and Technology* 179, no. 9 (2007): 1991-2037. https://doi.org/10.1080/00102200701386099

[52] Boehman, André L., Juhun Song, and Mahabubul Alam. "Impact of biodiesel blending on diesel soot and the regeneration of particulate filters." *Energy & Fuels* 19, no. 5 (2005): 1857-1864. https://doi.org/10.1021/ef0500585