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Deposits Formation, Emissions, and Mechanical Performance of Diesel Engine Fuelled with Biodiesel: A Review

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ABSTRACT

As the population and urbanization keep on growing at a rapid pace, fuel demands increase, and at the same time the natural fossil fuel resources are also depleting. To reduce the dependence on fossil fuel especially in transportation sectors, a more renewable source of energy, which is biodiesel is being implemented for various application in diesel engine. Biodiesel is capable of producing comparable engine performance as the mineral diesel. However, there are some arising problems including deposits issue, increased in emissions, and deterioration of overall engine performance when fuelled with biodiesel. In this study, a review of the deposits growth in the engine combustion chamber parts and its consequence impacts on the engine emissions and mechanical performance was carried out. Deposits existence and mechanism in the engine parts such as the injector nozzles and piston top, engine emissions such as hydrocarbon, carbon oxide, and nitrogen oxide, and engine mechanical performance such as the brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) were mentioned. Moreover, the experimental methods to investigate the performance of biodiesel and its comparison with ordinary diesel fuel were also presented in this paper. Finally, drawbacks of biodiesel need to be further investigated and understood in the future researches as biodiesel could become the primary replacement for petroleum diesel fuel worldwide.

Keywords: Biodiesel, combustion chamber, deposits, emissions, performance

1. INTRODUCTION

1.1 Biodiesel as an Alternative to Petroleum Diesel

The compression ignition (CI) or diesel engine is widely used because of its advantages such as high compression ratio, reliable operation, and economic value [1]. Compared to their gasoline counterparts, diesel engines are more superior in terms of thermal efficiency, power output, torque, and drivability [2]. Using petroleum diesel as its main fuel, CI engine applications in various sectors, especially in transportations, lead to several environmental issues. Growing population, rapid consumption, and rising demand for finite fossil fuels have caused the supply reserves to deplete, and consequently making petroleum fuel more limited and expensive [3]–[9]. Moreover, exhaust emissions from petroleum diesel usage have contributed to a large part of environmental pollution, such as greenhouse gas emissions to the atmosphere [10]–[12]. Besides polluting the environment, emissions such as particular matter could negatively impact human health and may deposits within the lungs [13].

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To deal with environmental issues, a cleaner form of energy that is renewable begins to gain attention and currently being developed by many countries. For diesel fuel in particular, alternative fuels, which are capable of replacing partly or wholly the high-demanded diesel fuel has now become the top priority among researchers. The number one candidate with high potential as an alternative to diesel fuel is biodiesel [14]–[16]. Biodiesel, which is also known for its chemical name as fatty acid methyl ester (FAME) is commonly produced from animal fats or vegetable oils via the transesterification process [17]–[20]. During the transesterification process, the mixture of fatty acids and alkyl esters, and glycerol are produced when triglyceride reacts with alcohol in the presence of strong acid or base as a catalyst [20]. This process will produce biodiesel yield, which can be used directly in diesel engines without any modification [12], [21]–[24].

Some of the most common biodiesel is derived from plants such as palm oil, jatropha curcas, soybeans, and rapeseed. The reason behind the popularity of biodiesel as an alternative fuel lies in its numerous advantages. Biodiesel is renewable, biodegradable, and non-toxic [7], [12], [16], [25]–[28]. Biodiesel also possesses similar properties to petroleum diesel, if not better [23], [25], [29]. Among typical advantages of biodiesel in terms of emissions is the reduction of combustion by-products, including carbon monoxide (CO), carbon dioxide (CO2), hydrocarbon (HC), nitrogen oxide (NOx), particulate matter (PM), and smoke [21], [29]–[32].

1.2 Biodiesel Deposits

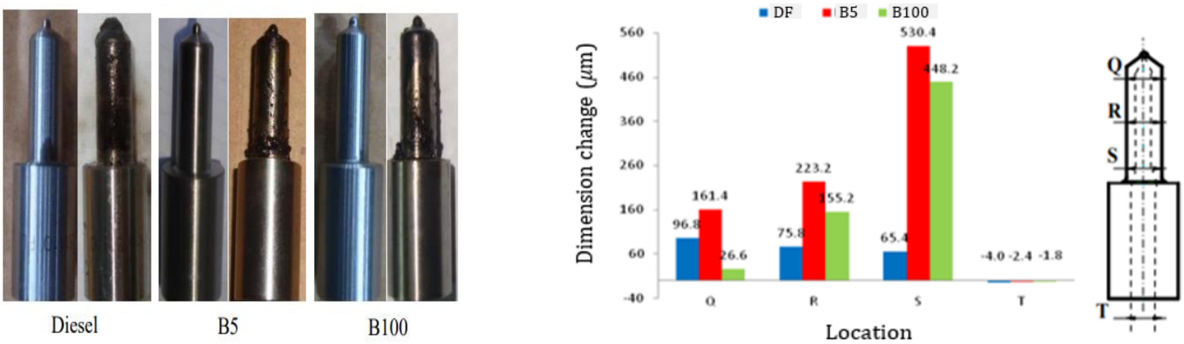
There are also drawbacks of using biodiesel as a fuel. Like every other fuel, biodiesel has its particular disadvantages on a diesel engine, and one of the common problems is deposits formation in the combustion chamber especially for biodiesel with high blend percentage. Other than that, application of biodiesel with high blend ratio in the engine could affect the transient characteristics and fuel system dynamics [33]. In the literature, researchers found that deposits formation in the combustion chamber of an engine is a complex process and phenomenon [34]–[37]. Due to various types of biodiesel blends, its deposits formation mechanism is far from being fully understood by researchers. Although most authors in the literature describe the benefits and negative impacts of biodiesel implementation in diesel engines, there is still a lack of information regarding deposits formation and effects on the diesel engine combustion system. Deposits or carbon deposits can be described as a heterogeneous mixture, where the mixture consists of ash, soot, colloidal organic matter.

Deposits presence on various parts of the engine will cause engine parameters to shift, such as air residue is decreasing, airflow becomes limited, compression ratio becomes higher, changes occur in spray characteristics, engine knock, decreasing thermal conductivity, and catalyst activity [34]. In the case of an engine operating in a short amount of time, biodiesel could provide a significant engine performance. On the other hand, on a longer engine operation, biodiesel may cause deterioration in engine performance, excessive formation of carbon and lacquer deposits, and damage to the engine as well [38]. Agarwal *et al.* [39] also stated that engine fuelled with neat vegetable oils or their blends with diesel could experience problems such as poor atomization characteristics, ring-sticking, injector-coking, injector deposits, injector pump failure, and lube oil dilution by crank-case polymerization if operating at a long period of times.

Furthermore, deposit formation frequently occurs on the injector part of diesel engine when biodiesel is used as the fuel. The existence of deposits on the injector causing blockage in the injector nozzle holes which lead to decrease in injection mass [40]. Moreover, the most common issue when using biodiesel is the formation of deposits on the injector nozzle as illustrated in Figure 1. From the figure, it can be observed that the most affected nozzle was the one with biodiesel (B5 and B100) compared to the ordinary diesel fuel. Other common problems associated with biodiesel application in diesel engine is presented in Table 1.

Table 1 Common Problems of Biodiesel Application [38]

Problem	Cause
Deposits in combustion chamber	Incomplete combustion of high boiling components
Plugging of fuel filter	Deposit of glycerin and alkali catalysts in fuel
Deterioration of cold start	Poor low-temperature fluidity
Exhaust of smoke at cold start	Exhaust of unburned elements
Degradation of fuel	Auto-oxidation of fuel
Degradation of rubber product	Auto-oxidation of fuel, swelling of rubber by oxygen



(a) (b)

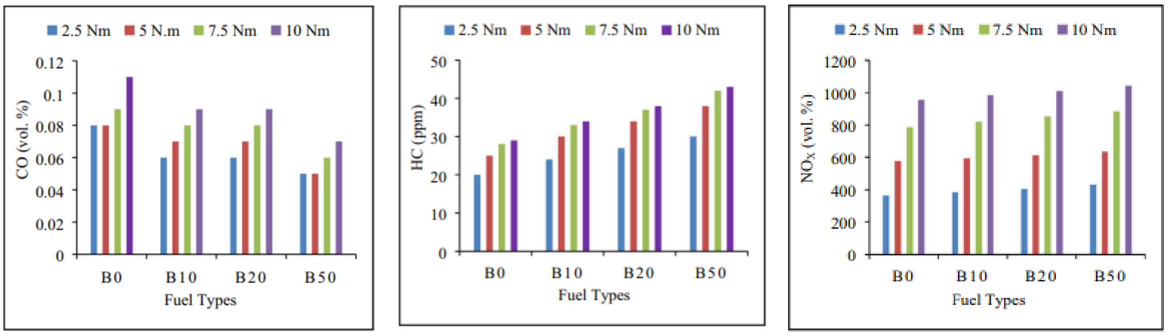
Figure 1. (a) comparison of carbon deposits on injector nozzle before (left) and after (right) endurance test (b) dimension change of nozzle house after endurance test. [41]

1.3 Effect of Biodiesel on Engine Emission Characteristics

The most common emissions of biodiesel that researchers in the literature discussed are CO, CO2, HC, NOx, PM, and smoke opacity. In the previous studies, researchers such as Sakthivel *et al.*, Vairamuthu *et al.*, and Senthil *et al.* [9], [25], [32] recorded that biodiesel blend produced a lower level of CO emissions compared to diesel fuel, especially at low blending ratio (<50% biodiesel blend). Furthermore, the emissions level decreased as the engine load increased. However, the CO emissions level could exceed that of diesel fuel when the engine runs longer, as investigated by Liaquat *et al.* [42]. In the case of CO2 emissions, the same trend as the CO was reported by Sakthivel *et al.* [32] where the CO2 emissions decreased as the engine load increased. However, the statement is in disagreement with Uyumaz *et al.* and Krishnamoorthi and Malayalamurthi [43], [44] who found that CO2 emissions increased as the engine load increased.

In general, biodiesel is capable of producing lower HC emissions compared to that of diesel fuel [45] and this statement is also in agreement with the studies done by Abedin *et al.*, Viswanathan and Thomai, and Deshmukh and Bhuyar [46]–[48]. For NOx emissions, the emissions level will increase with respect to the engine speed or load regardless of the type of fuel used as investigated by researchers in [8], [9], [25], [47] despite authors such as Sakthivel *et al.* and Alahmer *et al.* [32], [49] found that NOx emission decreased as the engine load increased. As being studied by Lapuerta *et al.* [50], when biodiesel increased in the fuel blend, the PM and smoke opacity decreased. Cheung *et al.* [45] also found that PM as biodiesel was lower than pure diesel. Pochareddy *et al.* and Hoang and Le [8], [51] in their studies stated that biodiesel blends generate less smoke opacity than diesel fuel although Vairamuthu *et al.* and Viswanathan and Thomai [25], [48] found the opposite in their experiment.

Figure **2** illustrates the comparison of CO, HC, and NOx emissions of cottonseed biodiesel (B10, B20, B50) with petroleum diesel (B0) at variation of engine loads (2.5Nm, 5Nm, 7.5Nm, 10Nm).



(a) (b) (c)

Figure 2. (a) CO, (b) HC, and (c) NOx emission of cottonseed biodiesel at variation of engine loads. [52]

1.4 Effect of Biodiesel on Engine Mechanical Performance

Biodiesel application in diesel engines could impact the engine in terms of its performance in various aspects. One of the most vital engine performance parameters is the BTE, as it indicates the efficiency of utilizing chemical energy in the fuel [8]. According to the literature, several authors found that when the engine load increased, the BTE also increased for all types of fuels, and BTE of the biodiesel tested was also comparable to that of diesel fuel [24], [46], [53]. In addition, Afzal *et al.* [54] also stated that biodiesel with higher kinematic viscosity will have greater reduction of BTE as high kinematic viscosity will result in irregular fuel atomization inside the combustion chamber where some fuel droplets remain unburnt hence decreasing the BTE. On the other hand, BSFC represents the efficiency of fuel by the ratio of fuel consumption and the effective power generated by the engine.

In general, BSFC for biodiesel is commonly higher compared to neat diesel fuel due to its lower heating value as investigated by Hoang and Pham, Abedin *et al.*, and Ong *et al.* [47], [55], [56]. Lower heating value of biodiesel is primarily influenced by the higher oxygen content in the biodiesel chemical composition. Thus, engine fuelled with biodiesel requires greater amount of fuel in order to produce the identical level of power output as the engine fuelled with petroleum diesel. Moreover, the effectiveness of the combustion process is related to thermal efficiency. Usually, the thermal efficiency of diesel fuel is superior compared to that of biodiesel, as being studied by Hoang *et al.* [57]. Since thermal efficiency is dependent on the BSFC, an increase in the latter could cause a reduction in the thermal efficiency of an engine. Furthermore, the lower heating value and higher viscosity of biodiesel attributed to the greater BSFC value compared to ordinary diesel fuel [41]. Lower viscosity and higher calorific value of ordinary diesel producing better combustion as the injected fuels are better atomized in the combustion chamber.

In this review, the causes and effects regarding to the deposits existence in the diesel engine combustion chamber when fuelled with biodiesel were discussed. The influence of biodiesel on combustion chamber deposits and its consequent impacts on engine emissions and mechanical performances were presented, as well as the existing experimental methods available to investigate the nature of deposits. Furthermore, this paper will provide additional knowledge to the current literature in understanding the complex phenomena of combustion chamber deposits.

2. METHODOLOGY OF DEPOSITS INVESTIGATION

2.1 Engine Bench Test

Researchers have developed various methods to investigate deposits formation in the combustion chamber. The most common experimental method used is the real engine test. From this test, researchers could observe and study the deposits growth in the engine parts such as piston top, injector, and cylinder head. Furthermore, a real engine test is capable of producing data on engine performance such as brake specific fuel consumption (BSFC), brake mean effective pressure (BMEP), brake thermal efficiency (BTE), and thermal efficiency. Other than that, emissions produced by the engine such as HC, CO, CO2, and nitrogen NOx could also be investigated.

In order to investigate deposit formation using short-term test which could be achieved in laboratory conditions, two type of tests were commonly used as being explained by Birgel *et al.* [58]. The first type of the engine bench test consisted of operating the diesel engine at different loads to study the change of temperatures of the injector tip. For the second type, the engine test was conducted at fixed speed and under constant load for a longer period of time. With these experimental methods, researchers were able to tell both the injector deposit level and the effect of deposits on the engine performance. However, this method has its disadvantages. Apart from its complexity, real engine test is also costly, requires a longer test duration, and facing a risk of engine damage. Thus, to stimulate deposits formation on a real engine, some researchers have developed other methods to stimulate deposits growth in the combustion chamber.

2.2 Hot Wall Surface Method

Apart from the actual engine test, the method to evaluate deposit formation is the heated wall surface method or hot surface deposition test (HSDT) that has been implemented by Suryantoro *et al.*, Yusmady and Arai, and Pham in their respective studies [34]–[36], [59]. This type of experimental study is focusing on the variable type of fuel or fuel properties, hot surface temperatures, and the droplet impingement intervals respectively. By applying this method, a particular test fuel, commonly diesel fuel and biodiesel is dropped on top of an aluminum plate, which is heated at certain temperature beforehand. Then, after the test reaches the desired number of fuel droplets, scanning electron microscopy (SEM) or/and energy dispersive spectroscopy (EDS) will be used to evaluate and analyze the components in the accumulated deposits [60]. Furthermore, this substitute method is used to evaluate the effect of droplet impingement intervals on the existence of the wet surface condition and the amounts of deposits generated by particular type of fuels [61]. Even though the hot wall surface method is more straightforward and cheaper, its main drawbacks are engine emissions and performance could not be investigated as in the actual engine test.

3. BIODIESEL DEPOSITS MECHANISM

3.1 Effect of Fuel Properties on Deposit Formation

One of the main factors that influence deposits formation is fuel properties. Fuel properties themselves have significant impacts on deposits formation in the combustion chamber. For biodiesel, some of its properties are less superior compared to petroleum diesel. Thus, biodiesel is more prone to issues that may lead to deposits formation [62]. Properties such as fuel density, kinematic viscosity, and lubricity could affect the mechanism of deposits formation, and each type of biodiesel has different properties depending on which sources it was extracted from. When pure biodiesel is used in diesel engines, impaired fuel spray penetration and poor fuel atomization will happen because of the inferior cold flow properties of viscosity and pour point of the biodiesel [23], [63].

Moreover, improper fuel atomization tends to occur for biodiesel as biodiesel possesses higher kinematic viscosity and lower calorific value as being stated by Afzal *et al*. [54]. Consequently, this factor will increase the accumulation rate of unburned fuels in the combustion chamber, which later turns to deposits. This statement is supported by Bi *et al*. [64] who mentioned that thin liquid fuel film and condensation occur effortlessly on the surface of the combustion chamber wall because of the high and narrow distillation range of biodiesel. Apart from that, biodiesel properties such as high kinematic viscosity could also deteriorate the efficiency of the fuel injection system, especially at a lower temperature as mentioned by Verma *et al*. [29]. In addition, the same author also emphasized that biodiesel is more challenging to be used at a lower temperature because of its poor cold flow properties compared to diesel fuel. This is also in agreement with Ali *et al*. [65] who mentioned that biodiesel possesses inferior pour and cloud point compared to neat diesel, which contributes to the poor cold flow properties of biodiesel. Moreover, high purity of biodiesel is also contributing to the deposit formation. As being stated by Shan *et al.* [66], during the transesterification process of biodiesel, the residual impurities including fatty acids, alcohol, glycerol, and catalysts could severely influence diesel engine through deposit formation, corrosion on engine parts, and fuel system failure.

3.2 Effect of Wall Temperature on Deposit Formation

The actual engine test to investigate the influence of surface temperature on deposits formation requires an extended test duration, complicated, and might even damage the engine. In order to overcome these difficulties, researchers have developed a heated wall surface method to stimulate deposits formation in a real engine in their studies. In a study by Yusmady and Arai [35], they found that the primary cause for the development of deposits is the wet/dry conditions, where for wet conditions the rate of deposits formation was greater compared to that of dry conditions. In another study by Pham [36], the author found that lower temperature resulted in more fuel being deposited on the heated wall surface and this is supported by Smith and Williams [67] who found out that deposits are initially formed on the injector nose which is the part with lowest temperature in the combustion chamber, followed by piston rings, cylinder wall, cylinder head, and piston crown.

In addition, this is in agreement with the finding reported by Suryantoro *et al*. [59] where the author found that more deposits were formed at 300°C than 350°C. It is also noticeable that the biodiesel (B100) formed more deposits compared to the neat diesel (B0) due to their different fuel properties. Furthermore, Pham [34], in his later study stated that the most critical factor leading to deposits formation is the wall temperature. Raza *et al*. [68] in their study investigated the effect of temperature on fuel droplets. They found that at high temperatures, fuel droplets of the identical size evaporate more quickly and concluded that vaporization time decreases whenever temperature increases and vice versa. Thus, when fuel droplets evaporate at a slower rate, deposits accumulation rate will increase prior to continuous fuel droplets.

3.3 Effect of Engine Parameters on Deposit Formation

The engine parameters also play an important role in deposits formation phenomena. Apart from fuel properties and wall temperature, the design of the combustion chamber itself contributes significantly to combustion chamber deposits formation [69]. Engine manufacturers are consistently finding ways to optimize their engine performance, and most of them are focusing on improving the injector to increase fuel injection quality. As being mentioned by Shu *et al*. [70], manufacturers are developing new injection systems in a diesel engine that could generate higher pressures and temperatures at the injector tips to improve fuel burning quality. However, this condition causing significant power loss and increased smoke emissions, as deposits are formed at and around the injector tip. Deposits formed inside the injector nozzle holes and/or outside the injector tip massively influence the injection pattern and rate of fuel flow. Consequently, this issue will impact the combustion process, fuel spray characteristics, and even affect overall system performance of engine [71].

In another study by Payri *et al*. [72], improvement on the fuel injection equipment (FIE) consists of advanced high-efficiency injectors with smaller holes. This geometry design leads to deterioration of torque and power loss as the smaller holes decrease the fuel flow area. Other than that, improved nozzles with honed entry and tapered nozzle holes will reduce the ability of deposits removal from the injectors. Moreover, deposit growth is also influenced by high temperatures at the injector tips and this leads to serious coking problem which will probably causing deposition of oxygenated hydrocarbon and auto-oxidation of hydrocarbons [73].

3.4 Deposits Growth in Combustion Chamber

Common parts in the combustion chamber that is most affected by deposits are the injector nozzle, injector tip, and piston [31], [74]–[78]. Apart from that, deposits are also formed on other mechanical parts in the combustion chamber such as the fuel filter, cylinder head, cylinder wall, piston ring, and control valves [79]–[85]**.** At the beginning of the deposits formation process, unburned fuel droplets were attached to the surface of the combustion chamber wall. A thin film is formed and some of the unburned fuel droplets will evaporate, while the remaining unburned fuel droplets turn into deposits. As the fuel injector is continuously spraying fuels into the combustion chamber, the process repeats and a new layer of deposits is formed on the top and around the initial deposits.

Furthermore, even after the engine has stopped, deposits may continue to develop due to fuel remains trapped within the nozzle holes and sac [86]. At some point in the engine operation, the rate of deposits formation will decrease. In the study by Caprotti *et al*. [87], they have found that after 80 hours of engine test, deposits formation still occurs, but the formation rate is lower than that at the early stage of the engine test. Birgel *et al*. [86] also stated that whenever a steady state condition between formation and removal of deposits is achieved, the deposits formation rate will decrease proportionally with the test duration. During deposits removal process, the deposited components are detached by physical, mechanical, and chemical mechanisms inside the combustion chamber [88]. Figure 3 shows different locations inside the combustion chamber that are exposed to deposits. As fuel is being injected into the combustion chamber via the injector, some of the injected fuels are not completely burned, causing it to impinge the surface of the piston, combustion chamber, and cylinder head. This process repeat over time and the unburned residual fuels will accumulate and deposits will be formed.

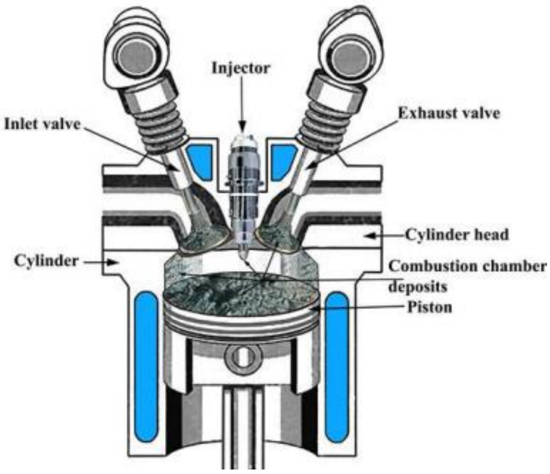


Figure 3. Deposit on different locations inside the combustion chamber. [34]

3.5 Deposits Composition

Carbon deposits are mostly originated from the fuel itself, and the remaining developed from lubricating oil [89]. Deposits formed in the internal combustion engine can be divided into three main classes as mentioned by Amara *et al.* [76]. Those main classes are carboxylate salt deposits, carbonaceous deposits, and lacquer deposit. The composition of deposits formed may vary according to factors such as their location in the combustion chamber, temperature, and type of fuel used. As can be seen in
Figure **4**, the SEM result shows that the deposits formed by preheated jatropha oil on the piston crown at position "a" was much more porous, while at position "b," black carbon deposits can be observed [56]. For different types of fuels, deposits formed on the same location may differ in physical properties because of the various properties of the tested fuel. This phenomenon has been observed by Suryantoro *et al.* [77], where they found that the deposits formed on the piston crown running with Indonesian biodiesel fuel (IBF) are dry. On the other hand, deposits of that running with B50 fuel tend to be wet.

In Figure 5, it can be seen that the deposit elemental compositions of the combustion chamber mechanical parts were dominated by carbon and oxygen content for both type of test fuels. This is in agreement with another research by Hidayat and Sugiarto [60], where they investigated the effect of temperature on the deposits mechanism formed by palm oil biodiesel with 30% biodiesel blend (B30) and hydrotreated vegetable oil (B30 HVO). They found out that all deposited layer locations indicated by the "A" and "B" location were dominated by carbon and oxygen elements as can be seen in Table 2. The weight ratio indicates that carbon elements were the most detected component by the SEM and EDS followed by oxygen elements and others. The deposits features of other fuels were further discussed as in

Table 3 and the emission and mechanical performance of the engine fuelled with various types of biodiesel were presented in Table 4.

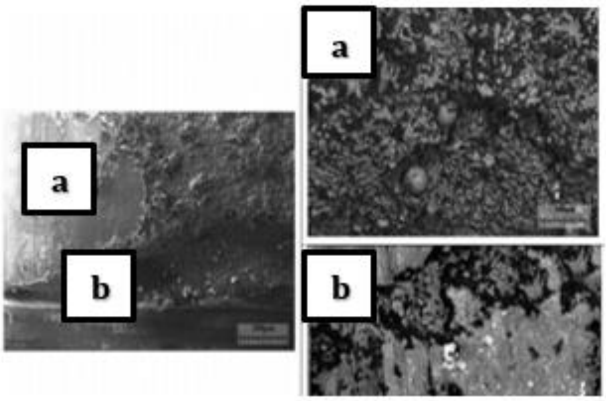
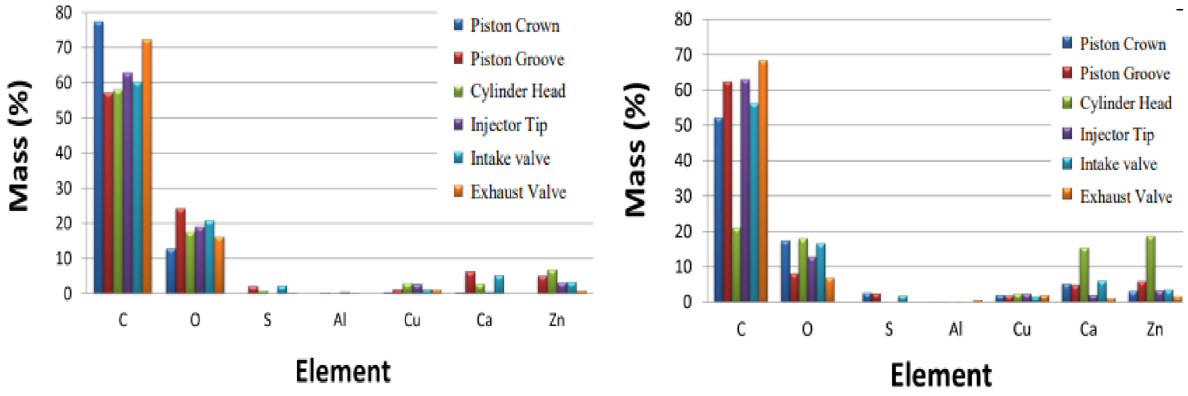


Figure 4. SEM of deposits on the piston crown. [56]



(a) (b)

Figure 5. Elemental composition of the deposits formed on different engine components using, (a) B50 (b) IBF. [77]

Table 2 Element Weight Ratio at Different Deposit Location [60]

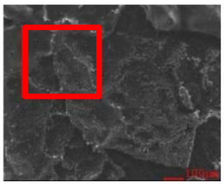
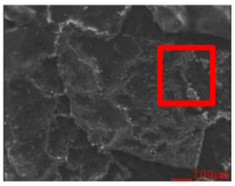
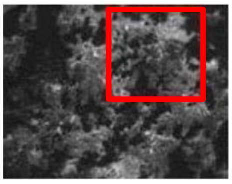
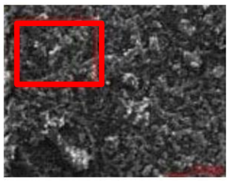
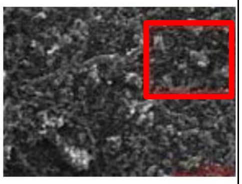
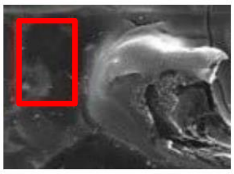
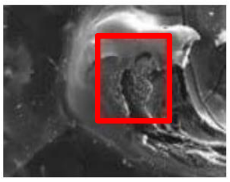
Fuel		**Temperature (°C)**			
		250		**350**	
B30	**Weight ratio (Wr%)**	 **A**	 **B**	 **A**	 **B**
	CK	57.35	56.00	54.03	50.01
	OK	36.71	37.31	26.85	20.29
	NK	3.80	4.03	3.80	3.02
	Others	2.14	2.66	15.32	26.68
B30 HVO	**Weight ratio (Wr%)**	 **A**	 **B**	 **A**	 **B**
	CK	60.11	60.89	53.38	48.95
	OK	30.85	29.55	38.97	44.29
	NK	4.04	2.51	2.20	6.58
	Others	5.00	7.05	5.45	0.18

Table 3 Deposit Mechanisms and Formation Characteristics

Authors	Fuel	Test Condition	Deposit Characteristics
Pham [34]	Diesel fuel (DF)	Heated wall surface method	The formation of a fuel liquid film and the amounts of deposits formed in an engine are different in value and location due to different mechanisms and temperatures on the surface of the combustion chamber wall
Yusmady and Arai [35]	Diesel fuel (DF)	Heated wall surface method	When droplet lifetime is longer than impingement interval, wet deposits are produced and vice versa
Pham [36]	Diesel fuel (DF)	Heated wall surface method	More deposits were formed at a lower temperature of the hot surface and vice versa
Husnawan *et al.* [37]	20% palm oil biodiesel emulsified with water (0%, 5%, 10% 15%)	Yanmar L100AE-DTM diesel engine 25h endurance test	The presence of water reduces the degree of endothermicity of deposits Increase with increasing percentage of water in the emulsified fuel
Agarwal *et al.* [39]	Linseed oil and diesel fuel (DF)	CI Diesel engine 512h endurance test	Less for 20% linseed oil biodiesel blend (512h engine operation) compared to DF (200h engine operation) Less for 40% for 20% linseed oil biodiesel blend compared to DF Less for 20% linseed oil biodiesel blend compared to DF Similar results were also noticed for deposits formation on piston ring grooves, intake, and exhaust valves
Reksowardojo *et al.* [41]	Rubber seed oil biodiesel (RSB100, RSB5) and diesel fuel (DF)	Natural Aspiration diesel engine Endurance test with speed variations	Higher for RSB100 followed by RSB5 and DF Injector surface was dirtier and carbon deposits were much thicker for RSB100 and RSB5 compared to DF
Liaquat *et al.* [42]	Palm oil biodiesel (PB20) and diesel fuel (DF)	DI diesel engine 250h endurance test	Oily/greasy deposits were observed for DF while for PB20 the deposits were dry Lower for DF compared to PB20 A different area on the surface of the injector contains different deposits composition For PB20, deposits formed at the tip and around the injector tip were relatively thick and it caused shrinkage in the diameter of the nozzle holes
Hoang and Le [51]	Jatropha oil (preheated SJO90, SJO30) and diesel fuel (DF)	Yanmar TF120M diesel engine 300h endurance test	Higher for SJO30 compared to SJO90 and DF
Hoang and Pham [56]	Preheated Jatropha oil (SJO90) and diesel fuel (DF)	Yanmar TF120M diesel engine 300h endurance test	SJO90 produced dry deposits on the piston Higher for SJO90 compared to DF

Hoang *et al.* [57]	Unpreheated and preheated jatropha oil (SJO30 and PSJO90) and diesel fuel (DF)	Yanmar TF120M diesel engine 300h endurance test	Higher for SJO30 and PSJO90 compared to DF
Suryantoro *et al.* [59]	Biodiesel (B100) and diesel fuel (DF)	Heated wall surface method	B100 produced more deposits compared to DF
Hidayat and Sugiarto [60]	Palm oil biodiesel (B30) and hydrotreated vegetable oil (B30 HVO)	Heated wall surface method	The deposit structure in B30 is black with white spots rough, and dry spots, while B30 HVO tends to be wet, smooth and not porous Mass of the deposit at B30 HVO is less than the fuel using B30
Suryantoro *et al.* [77]	Biodiesel (B50) and Indonesian biodiesel fuel (IBF)	Yanmar L48N diesel engine 200h endurance test	Injector tip deposits produced by IBF were hard, dry, and more brittle compared to that produced on the cylinder head or piston crown For B50, the deposits were thicker, relatively soft, and wet/oily compared to IBF Some deposits were shed off the injector surface after 100h of engine operation
Suryantoro *et al.* [80]	Palm oil biodiesel (B100) and diesel fuel (DF)	Heated wall surface method	More deposits were formed at a lower temperature of the hot surface and vice versa Deposits produced by DF were dry while B100 were wet
Birgel *et al.* [86]	Vegetable cooking oil (B100, B30) and diesel fuel (DF)	CI diesel engine 31h engine run test	A higher blend of biodiesel produced higher amount of deposits Higher for B30 and B100 compared to DF
Caprotti *et al.* [87]	Diesel fuel (DF) added with 1ppm and 3ppm Zinc (Zn)	Diesel engine 16h run test	The growth of injector deposits was dependent on the fuel quality and fuel type Rate of deposits formation decreased after 80 hours run test, but some deposit is still forming
Lepperhoff and Houben [88]	Diesel fuel (DF)	-	Deposits structures depend on the location and temperature level Black carbon, wet hydrocarbon portions, and tar-like components (<200°C) Dry porous soot and the presence of lacquer coating (200°C-300°C) Thinner deposits layer in lighter color (>300°C)
Arifin *et al.* [90]	Palm oil biodiesel and diesel fuel (DF)	Heated wall surface method	Wet conditions have a higher impact on deposits development for BDF compared to DF
Mulyono *et al.* [91]	Palm oil biodiesel (B20, B30)	Heated wall surface method	Mass of deposits accumulated were highest for B30 followed by HVO B30 and B20 at every test temperature

	and hydrotreated vegetable oil HVO B30		
Kalam and Masjuki [92]	Crude palm oil (CPO) emulsified with 1%, 2%, and 3% of water and diesel fuel (DF)	Yanmar diesel engine 100h endurance test	More deposits formed when using preheated CPO compared to DF and CPO emulsified fuels Volatile deposits composition decreased when water in CPO increased Ash deposits composition is higher for preheated CPO followed by CPO emulsified fuel and DF
Cheng [93]	Toluene, isooctane, and indolene	Waukesha Cooperative Research Fuel (CFR) engine 20h run time	Variations of surface temperature resulted in different morphology of deposits formed in different parts of the combustion chamber
Clear *et al*. [94]	Diesel fuel (DF) tested with different types of additives	Diesel engine run test L10 injector depositing test	Deposits formation tendency is influenced by the fuel quality Deposits formation for fuel treated with additive is lower compared to the untreated base fuel
Bari *et al*. [95]	Crude palm oil (CPO) and diesel fuel (DF)	Yanmar L60AE-D 500h endurance test	Heavy black carbon deposits were formed on the engine head, piston crown, and piston bowl when CPO was used Deposits formed on the injector nozzle tip deteriorated the fuel spray quality – less misty spray and uneven spray distribution Deposits formed at the piston and piston rings contributed to wear on these parts
Hoang and Pham [96]	Preheated jatropha oil (PJO90) and diesel fuel (DF)	D243 diesel engine 300h endurance test	Engine running on PJO90 contributed to more deposits growth compared to DF Deposits formed at the piston crown and piston groove contain different features which were gel-like and sticky deposits, porous deposits, and hard deposits
Hoang *et al*. [97]	Preheated jatropha oil (PJO90) and diesel fuel (DF)	Yanmar TF120M diesel engine 300h endurance test	Deposits produced on the injector tip by DF were observed to be oily/greasy, whereas deposits were dry for PJO90 Higher for PJO90 compared to DF after 300h of engine operation
Tziourtzioumis and Stamelos [98]	Biodiesel (B70) and diesel fuel (DF)	HSDI turbocharged diesel engine Endurance test with load variations	Heavy deposits at the injector nozzle and injection holes Heavy quantity of dense slurry rich in fatty esters in the fuel filter

Table 4 Emission and Mechanical Performance Characteristic of Diesel Engines with Biodiesel

Authors	Biodiesel	Test Condition	Increase/Decrease vs Diesel Fuel						
			CO	HC	NO_x	Smoke/PM	BSFC	BTE	Brake Power
Husnawan *et al.* [37]	20% palm oil biodiesel emulsified with water (0%, 5%, 10% 15%)	Yanmar L100AE-DTM diesel engine 25h endurance test	↑	-	↓	-	-	-	-
Reksowardojo *et al.* [41]	Rubber seed oil biodiesel (RSB100, RSB5)	Natural Aspiration diesel engine Endurance test with speed and load variations	↑ (RSB100) ↓ (RSB5)	↑ (RSB100) ↓ (RSB5)	-	↑ (RBS100, RSB5)	↑	-	↑
Liaquat *et al.* [42]	20% biodiesel blend (PB20) of palm oil	DI diesel engine 250h endurance test	↓ at the first hour ↑ after 250h	↓ at the first hour ↑ after 250h	↑ at the first hour ↑ after 250h	↑	-	-	-
Deshmukh and Bhuyar [46]	Balanites oil	Kirloskar diesel engine Load variations	↓	↓	Slightly similar	↓	↑	↓	-
Hoang and Le [51]	Prheheated jatropha oil (SJO90, SJO30)	Yanmar TF120M diesel engine 300h endurance test	↑ (SJO30)	↑ (SJO30)	↓ (SJO30)	↑ (SJO30)	↑ (SJO30)	↓ (SJO30)	-
Agbulut *et al.* [52]	Cottonseed oil biodiesel (B10, B20, B50)	Lambordini 15 LD350 diesel engine Load variations	↓	↑	↑	-	↑	-	-
Afzal *et al.* [54]	Biodiesel (B50, B65, B80)	Kirloskar TV-1 diesel engine Load variations	-	-	-	-	↑	↓	-
Hoang and Pham [56]	Preheated Jatropha oil (SJO90)	Yanmar TF120M diesel engine 300h endurance test	↑ after 300h	↑ after 300h	↓ after 300h	↑	↑	-	-
Hoang *et al.* [57]	Unpreheated and preheated jatropha oil (SJO30 and PSJO90)	Yanmar TF120M diesel engine 300h endurance test	↓	↓	Slightly similar	↓	-	-	-
Kalam and Masjuki [92]	Crude palm oil (CPO) emulsified with 1%, 2%, and 3% of water	Yanmar diesel engine 100h endurance test	↓ (preheated CPO) ↑ (emulsified CPO)	↓ (preheated CPO)	↑ (preheated CPO) ↓ (emulsified CPO)	↓	-	-	-
Bari *et al.* [95]	Crude palm oil (CPO)	Yanmar L60AE-D diesel engine 500h endurance test	↑	-	↑	-	↑	↓	-
Hoang and Pham [96]	Preheated jatropha oil (PJO90)	D243 diesel engine 300h endurance test	↑	-	↑	-	-	-	-
Hoang *et al.* [97]	Preheated jatropha oil (PJO90)	Yanmar TF120M diesel engine 300h endurance test	↑	↑	↓	-	-	-	-
Kalam and Masjuki [99]	Palm oil biodiesel	Isuzu 4FBI diesel engine 100h endurance test	-	↓	↓	-	-	-	↑
Chiavola and Recco [100]	Waste cooking oil biodiesel (B20, B40)	LWD 442CRS diesel engine Speed variations at 80% load	↑ (3000rpm)	↓	↓	↓	No significant changes	-	-

Ors *et al.* [101]	Safflower oil (SB3, SB20), bioethanol blend (SB3BE5, SB3BE10, SB20BE5, SB20BE10),	Antor 3LD510 diesel engine Load variations	↑ (SB3, SB20) ↓ (SB3BE5, SB3BE10, SB20BE5, SB20BE10)	↓ (SB20) ↑ (SB3BE10)	↓ (SB20) ↑ (SB3BE10)	↑ (SB20)	↓ (SB20)	-	-
Sidibe *et al.* [102]	Pure jatropha oil (PJO), preheated jatropha oil (HJO)	LOMBARDINI 9LD56/2 diesel engine Load variations	↑ (80% engine load)	-	↑	-	No significant changes	-	-
Noor *et al.* [103]	Palm oil biodiesel (B10, B20, B30)	Cummins-NT855 diesel engine Speed variations (with/without steam injection)	↓	-	↑	-	↓ (steam injection)	-	↑ (without steam injection)
Ramasamy *et al.* [104]	Palm oil biodiesel	Kubota RT-125 diesel engine Speed variations	↓	↑	↓	-	↑	↓	-
Ghobadian *et al.* [105]	Waste vegetable oil (B10, B20, B30, B40, B50)	RD270 Ruggerini diesel engine Speed variations	↓ (full load)	↓ (full load)	-	-	↑ (full load)	-	-
Saravanan *et al.* [106]	Pine oil biodiesel	4-stroke water cooled diesel engine Load variations	↓	↓	↑	↓	↓	↑	-
Karthickkeyan [107]	Pumpkin seed oil biodiesel	Kirloskar/TV1 water cooled diesel engine Load variations	↑	↑	↑	↑	↓	↑	-
Suhaimi *et al.* [108]	Hexanol and ethanol diesel blend	Yanmar TF120M diesel engine Load variations	↑	↓	↑	-	↓	↑	-
Lin and Lin [109]	Soybean biodiesel	4-stroke diesel engine Speed variations	↓	-	↓	-	↓	↑	-
Dorado *et al.* [110]	Waste olive oil biodiesel	Perkins AD 3-152 diesel engine Load variations	↓	↑	↓	-	↑	-	-

4. CONCLUSION

In this paper, biodiesel performance and deposits formation in diesel engine has been summarized according to the published literature from various authors. From the literature, it is evidently proved that the existence of deposits in the combustion chamber is impossible to eliminate, regardless of the types of neat diesel or biodiesel used in the engine. As fuel is injected into the combustion chamber, it is likely not to be burned entirely or fully evaporated, and this issue as stated in the literature is caused by factors such as the fuel properties itself, the engine parameters, and temperature inside the combustion chamber. Furthermore, the studies using the heated wall surface method show that deposits generated possess different mechanisms, depending mainly on the heated surface temperature and the fuel impingement interval. Such a situation can be related to the actual engine test, where deposits growth on parts such as the piston crown, cylinder head, and injector would have different deposits characteristics because of the temperature difference on those parts when the engine is operating. In addition to the deposits issue, emissions and mechanical performance of the diesel engine were also stressed by authors in the literature. In the literature, most authors found that the emissions characteristic and engine mechanical performance when the engine is fuelled with biodiesel is comparable to diesel fuel. However, some authors found that biodiesel still lacks performance reliability in some areas compared to ordinary diesel fuel. With the current technologies in engine combustion chamber system, deposits seem to be the main issue faced by the engine manufacturer for a long time. Improvement must be made primarily in the fuel properties of biodiesel in order to optimize the biodiesel performance, before moving to engineer a more effective engine combustion chamber. Thus, it can be concluded that research on biodiesel performance and deposits in an engine is still inadequate. Further study and development are vital to make biodiesel one of the long term replacements for petroleum diesel fuel.

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