Evaluation of the performance and emissions of a single cylinder diesel engine fueled by biodiesel and using exhaust gas recirculation

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Abstract: In this study, the effect of using biodiesel – derived from waste cooking oil – and exhaust gas recirculation (EGR) on engine performance and emissions of a single cylinder 4-stroke engine has been investigated. Three engine speeds (1800, 2100 and 2400 rpm), three engine loads (25%, 50% and 75%), four biodiesel/diesel blend (B0, B5, B10 and B15) and four EGR rates (0%, 10%, 20% and 30%) have been applied to the engine. The considered emissions of the engine, measured at exhaust, were NO_x, CO, CO_2, HC and smoke. The considered performance parameters were engine power, exhaust gas temperature and brake specific fuel consumption. The results of the study show that the addition of the biodiesel to the diesel fuel increases NO_x emission of the engine. The highest decrease in NO_X emissions while using the biodiesel and EGR was 63.76% with B10 fuel blend and 30% EGR rate. Therefore, it can be stated that, using EGR, the increase of NO_x emissions in the engine due to biodiesel can be reduced. The simultaneous usage of EGR and biodiesel reduced CO emission of the engine of 4.04%, 12% and 1.73% for low, medium and high engine speed. The biodiesel decreased the HC emission of the engine and so it compensated the increase of HC due to EGR. The highest reduction in HC emission levels was 54.05% while using EGR and biodiesel simultaneously. It is noticeable that the total amount of the smoke emission levels while using EGR and biodiesel did not change considerably.

Keywords: EGR, biodiesel, emission, ci engine

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1 Introduction

One of the most interesting research area currently investigated in the field of internal combustion engines is to define and test new sources of primary energy. This is due to exhaustion of fossil fuels reserves, associated to health and environmental problems determined by them (Suh and Lee, 2016). Biodiesel is an alternative fuel widely accepted as a substitution for diesel fuel. The most significant aspect of the biodiesel is its similarity to diesel fuel. Biodiesel has characteristics so close to diesel fuels so that can be used in compression ignition engine without any engine modification. Biodiesel is a renewable source of energy and, in addition, in most cases it comes from waste material; therefore, it represents a good way to reuse waste materials (Ghobadian, 2012; Safieddin et al., 2011). Biodiesel contains about 10% to 12% oxygen content and therefore it can be also used as an oxygenate additive.

The researches on using of biodiesel in internal combustion engine have revealed that CO, CO_2, smoke and HC raw emissions are generally decreased using the biodiesel. On the other hand, NO_x emissions levels usually increase, mainly due to the oxygen content of the biodiesel (Suh and Lee, 2016; Ghazali et al., 2015).

In compression ignition engines, NO_x emission levels are significant, due to sufficient availability of oxygen and high temperature. On the other hand, compression ignition engines offer several advantages, most of all a significant fuel saving. Therefore, the research on

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reduction of NO_x using biodiesels has become one of the most popular researches in the engine field.

Different technologies and methods have been introduced and tested to decrease the additional NO_x deriving from biodiesel utilization. The principles of these methods are to lowering the combustion temperature or remove some of the oxygen from the cylinder. Water addition for cooling the cylinder content during combustion has been applied either adding water to the fuel as an emulsion or injecting water into the cylinder (Ithnin et al., 2015). Another widely used method is to recirculate a portion of the exhaust gases along the intake duct. This method, known as EGR, is effective in reducing the average temperature in the cylinder (Pedrozo et al., 2016).

Although EGR is a useful method to reduce NO_x engine-out emissions, smoke emissions are increased (Rajesh and Saravanan, 2015). Combining EGR and biodiesel utilization, it is commonly recognized that an increase in CO, HC and smoke emissions due to EGR (Nabi et al., 2006) and in NO_x due to biodiesel is obtained (Sanjid et al., 2016). On the other hand, it is stated that the increase of NO_x emission levels coming from biodiesel utilization can be compensated using EGR (Pradeep and Sharma, 2007). Research activity is therefore addressed on the determination of the optimal EGR rate allowing a good trade-off between NO_x and smoke emissions. It is commonly believed that 15%-20% of EGR rate is a suitable range (Agarwal et al., 2011; Maiboom et al., 2009; Mani et al., 2010; Pradeep and Sharma, 2007). However, the application of the EGR system on a small CI engine is not widely discussed in literature and there is not a comprehensive research on the performance parameters and emissions of a CI cylinder engine while using biodiesel.

Therefore, aim of this study is to discuss the utilization of an EGR system to decrease NO_x emission levels emitted by a single cylinder CI engine while using biodiesel in blend with traditional diesel fuel. In particular: 1) the performance parameters and exhaust emission levels of a single cylinder engine while using EGR system and biodiesel fuel will be investigated; 2) the appropriate EGR rate leading to best NO_x-smoke trade-off will be found.

The factors varied during experimental campaign were engine load (25%, 50% and 75% full load), engine speed (1800, 2100 and 2400 rpm), percent of biodiesel in biodiesel/diesel blend (B0, B5, B10 and B15) and EGR rate (0%, 10%, 20% and 30%).

2 Materials and methods

2.1 Specifications of the produced fuel

Biodiesel is a methyl or ethyl ester made from vegetable oils or animal fats. It can be used as fuel in diesel engines or other thermal systems with no system modifications because it presents characteristics similar to fossil fuels. Biodiesel is typically produced through the reaction of a vegetable oil or animal fat with methanol in the presence of a catalyst to yield glycerin and methyl esters (Testing and Materials, 2009). The biodiesel fuel used in the current research was produced from waste cooking oil in Renewable Energy Laboratory of Tarbiat Modares University, Tehran, Iran. The standard diesel fuel was the common fuel used for diesel engines in Iran. Some important characteristics of the produced biodiesel fuel along with the related standards, together with the characteristics of traditional diesel fuel, are reported in Table 1.

Table 1 Some important characteristics of the produced biodiesel fuel along with the related standards

Specification	Standard test method	Allowable range	Biodiesel	Diesel	Unit
Kinematic viscosity	EN 14214	3.5-5	4.72	3.5	mm^2/s
Density	EN 14214	----	0.862	0.837	g/cm^3

2.2 Specifications of tested engine and dynamometer

Table 2 reports the main specifications of the engine tested during experimental campaign. In order to measure the engine torque, speed and output power, an eddy-current dynamometer (Schenk, Germany) was used. The dynamometer is able to measure power, rotational speed and torque up to 21 hp, 10000 rpm, and 80 Nm, respectively. The accuracy of the dynamometer was in the range of 0.5%-1%. An overall view of the engine test setup is shown in Figure 1.

2.3 EGR system

The EGR system used in this study was a cooled EGR system. The EGR cooler and other parts of the system can be seen in Figure 1. The EGR cooler was a tube-pipe cooler (Figure 2). To measure the EGR rate of the engine, the following Equation (1) has been used (Lattimore et al., 2016).

$$\text{EGR ratio} = \frac{CO_{2(int)} - CO_{2(amb)}}{CO_{2(exh)} - CO_{2(amb)}} \times 100 \qquad (1)$$

where, $CO_{2(exh)}$, $CO_{2(int)}$ and $CO_{2(amb)}$ are the% CO_2 measured respectively at then engine exhaust, intake port and in the ambient. The EGR rate has been regulated by a valve.

Table 2 Specifications of the evaluated engine

3LD 510	Model
Lombardini, Italy	Manufacturer
1	Number of cylinders
90 mm	Stroke
85 mm	Bore
510 cm^3	Displacement
12.2 hp (9 kW)	Rated output power (@3000 rpm)
33 Nm	Rated output torque (@1800 rpm)

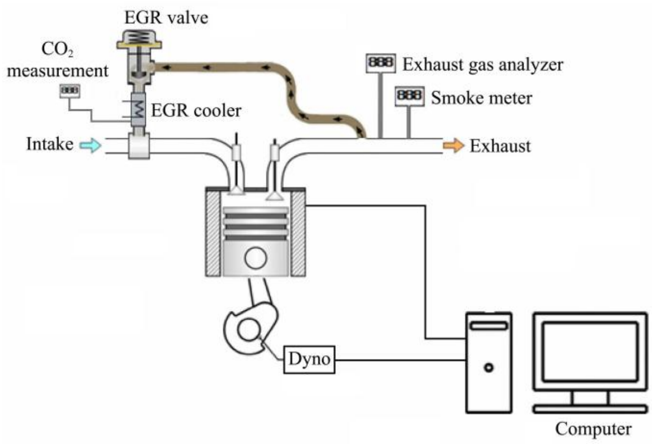


Figure 1 Engine test set up

Figure 2 Homemade EGR cooler

2.4 Fuel consumption measurement system

The system consisted of a fuel tank, conjunctions, and pipes for fuel transporting, sensor to measure the volume of fuel, thermal transducers of the returned fuel, fuel pressure transducers, fuel pressure gauge and fuel temperature sensor. The measuring accuracy of the system was ±1 cm^3 h^{-1}. The system had two digital monitors for displaying fuel temperature in terms of ℃ and fuel consumption in terms of L h^{-1}. The system is equipped with fuel tank pressure controller to increase the accuracy of fuel consumption measurement.

2.5 Specifications of exhaust emissions analyzer

In order to measure the engine-out emissions, an AVL DITEST GAS 1000 exhaust emission analyzer was used. This device measures CO and CO_2% vol. as well as HC ppm using infrared technology. The device could also determine O_2% vol. and NOx ppm using chemical sensors. Interfacing the device with AVL DISmoke 480 BT smoke opacimeter, it was also possible to characterize the smoke emission. The measurement accuracy and other characteristics of the analyzer are reported in the Table 3.

Table 3 The accuracies of the measurements and the uncertainties in the measured results

Measured	Resolution	Accuracy
CO	0.01% vol.	<10.0% vol.: ±0.02% vol ≥10.0% vol:
CO_2	0.01% vol.	<16.0% vol.: ±0.3% vol. ≥16.0% vol
HC	≤2.000 : 1 ppm vol.	<2000 ppm vol.: ±4 ppm vol ≥5000 ppm vol ≥10000 ppm vol
O_2	0.01% vol.	±0.02% vol.
NO_x	1 ppm vol.	±5 ppm vol.

2.6 Methods and steps of experiments

The experiments were carried out in an engine test cell. The engine has been run up to reach steady state condition (70℃ oil temperature) while fueled by the standard diesel in idle condition. Then the fuel in the tank was replaced by the test fuel blends and engine run with that up to replacing all of the fuel in the engine. After that, the engine was tested at different loads (25%, 50% and 75%) and speeds (1800, 2100 and 2400 rpm). To determine amount of the engine load, the engine has been run in full load in engine steady state condition. Then the torque of the engine in this conditioned has been recorded and the amount of the engine load for each test has been determined in term of this maximum torque of the engine in the full load. Furthermore, three different values of the EGR rate (10%, 20% and 30%) were applied for each fuel blend-engine speed-engine load condition by adjusting the EGR valve. The value of EGR rate was calculated measuring the CO_2 in ambient, intake and exhaust line of the engine by means of AVL DITEST GAS 1000 and then applying Equation (1). Each test has been replicated three times.

3 Results and discussion

Table 4 shows the descriptive statistics of the result of the experiments. As it can be seen in this table, standard error for brake specific fuel consumption (BSFC) is very high. This comes from the very high value of the BSFC in lower engine speed and load, especially in 1800 rpm engine speed and 25% engine load. In this condition, amount of the engine power is very low and as it is well known BSFC calculated by the dividing of the fuel consumption to the engine power. So the result of this calculation for this condition is very high.

In the Table 5 the multivariate test of significance is shown. As it can be seen in this table all main factor has a significant effect on the engine parameter in significance level of 0.05. But the interaction of these parameters has not a statistically significant effect on the engine parameter in significance level of 0.05.

Table 4 Descriptive statistics of the data

	Valid N	Mean	Minimum	Maximum	Variance	Std.Dev.	Standard Error
Power	146	2.187	0.83	4.15	1	0.975	0.0807
SFC	146	1418.391	229.8688	17680.28	10564745	3250.345	269.0005
Exhaust Tem.	146	229.663	101	444	7767	88.131	7.2938
k [m^{-1}]	146	7.662	1.79	16.3	20	4.507	0.373
CO [%vol]	146	0.783	0.1	2.57	0	0.657	0.0544
CO_2 [%vol]	146	5.53	2.3	9.46	3	1.8	0.149
HC [ppm]	146	99.062	17	289	4357	66.008	5.4629
NO [ppm]	146	225.404	54	393	7102	84.276	6.9747

Table 5 ANOVA result of the considered factor

	Value	F	Effect-df	*p*
Intercept	0.000001	626727.2	2	0
{1}Fuel Type	0.000004	167.2	6	0
{2}EGR rate	0.000074	38.3	6	0
{3}Engine Speed (RPM)	0.000127	44	4	0.02
{4}Engine Load (%)	0.000998	15.3	4	0.06
Fuel Type*EGR rate	0.000029	20.3	18	0.04
Fuel Type*Engine Speed (RPM)	0.000326	9.1	12	0.1
EGR rate*Engine Speed (RPM)	0.001924	3.6	12	0.24
Fuel Type*Engine Load (%)	0.000342	8.8	12	0.11
EGR rate*Engine Load (%)	0.000202	11.6	12	0.08
Engine Speed (RPM)*Engine Load (%)	0.010745	2.2	8	0.35
Fuel Type*EGR rate*Engine Speed (RPM)	0.000088	5.9	36	0.16
Fuel Type*EGR rate*Engine Load (%)	0.000083	6	36	0.15
Fuel Type*Engine Speed (RPM)* Engine Load (%)	0.001496	2.1	24	0.38
EGR rate*Engine Speed (RPM)* Engine Load (%)	0.001181	2.3	24	0.34
1*2*3*4	0.00014	2.3	72	0.35

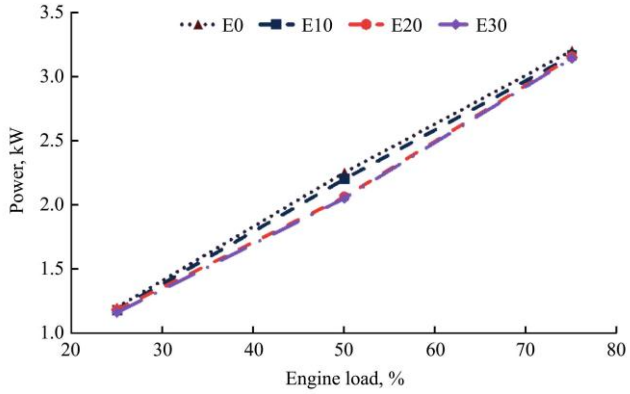
3.1 Performance parameters

3.1.1 Power

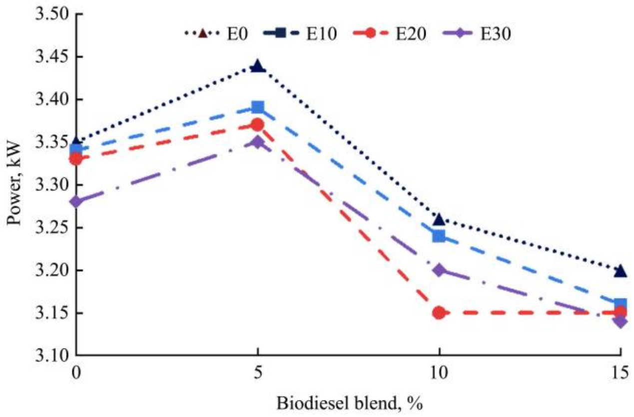
The Figure 3a shows the variation of the engine power (kW) in different engine load for different fuel blends. As shown in the Figure 3a, Increases of the engine power (kW) with the increase in the engine load were almost linear. In addition, the power has been decreased while increase in the EGR rate. This trend was same in all engine speeds. The highest decrease in engine power due to using EGR is for B15 fuel blend, 2100 rpm engine speed, 25% engine load and 30% EGR rate.

The Figure 3b shows the variation of the engine power for different biodiesel blends and EGR rate in 1800 rpm engine speed and 25% engine load. The engine power has been increased while fueling with B5 for all of the EGR rate. Then it has been decreased for B10 and B15 fuel blends. The rate of reduction for B10 is higher than that for the B15. Same results have been reported by other researchers (Buyukkaya, 2010; Gumus, 2010).

The power increases with increasing the engine speed and then decreases with further increasing engine speed for all fuel blends. For 5% of the biodiesel, the engine power has been decreased but not significantly. The power of the engine has been increased with increase in percent of biodiesel in diesel biodiesel fuel blend. In other hand, the increase in the EGR rate has decreased power of the engine. The highest drop in the engine power is 31.97% for 2100 rpm engine speed and 25% engine load. However, the average of the engine power for all engine working condition has been increased 4.03%. In higher engine loads (75%), for all engine speeds, amount of the power reduction has been more than that in lower engine loads (25% and 50%). The reason for this is lower heating value of the waste cocking oil. It means that higher value of biodiesel blend fuel is required to reach same power as the diesel. Some reason for increase in engine power by addition the biodiesel to diesel are the about 10% oxygen content of biodiesel and also its higher density and viscosity. The oxygen content of biodiesel can increase the quality of combustion special in rich zone and increase the engine power. The higher density and viscosity of the biodiesel increase the mass flow rate and decrease leakage during sending fuel from pump to injector, respectively (Buyukkaya et al., 2013).



a. Effect of engine load (%) and EGR rate (%) on engine power (kW) in 1800 rpm engine speed and B15 fuel blend

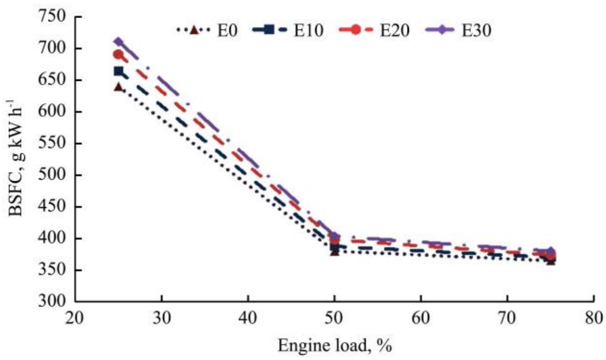


b. Effect of biodiesel (%) and EGR rate (%) on engine power (kW) in 1800 engine speed and 75% engine load

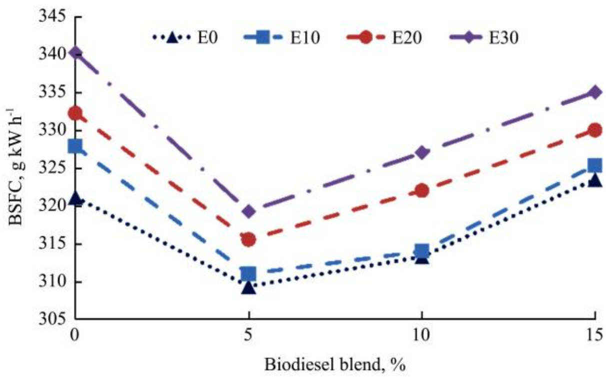
Figure 3 Effect of engine load and EGR rate on engine power

3.1.2 BSFC

Figure 4a shows the variations in BSFC (g kW h^{-1}) at different engine loads and 1800 rpm engine speed for various EGR rates. The BSFC has been decrease with increase in the engine load. The reduction of the BSFC from 25% to 50% engine load is more significant than that from 50% to 75% engine load. In addition as it can be seen in this figure, the increase of the biodiesel percent in diesel biodiesel blend fuel has increased the amount of the BSFC. The highest increase in BSFC is 47.53% in 75% engine load, 2400 rpm engine speed, B15 and 30% EGR rate. All fuel blends with the EGR application showed similar trends when compared with diesel fuel without EGR.



a. Effect of engine load (%) and EGR rate (%) on engine BSFC (g/kWh) in 1800 rpm engine speed and B15 fuel blend



b. Effect of biodiesel (%) and EGR rate (%) on engine power (kW) in 1800 engine speed and 75% engine load

Figure 4 Effect of engine load and engine power on engine BSFC

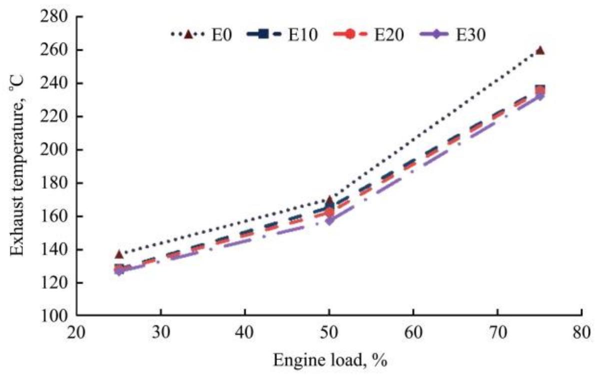
Figure 4b shows the effect of the increase of the biodiesel percent in diesel biodiesel blend on the BSFC (g kW h^{-1}) for different EGR rate and in 75 engine load and 1800 rpm. As can be seen in this figure, the BSFC has been decreased due to using of biodiesel. The trends of graph for all of the EGR rates were similar. The lowest value of the BSFC has been for B5 biofuel blend and the BSFC has been increased from B5 to B15 approximately as a straight line. The density of the biodiesel fuel used in this study was approximately 2.99% higher in comparison to diesel fuel. Therefore, it is more fuel mass flow rates required to provide the same engine effective output and results in higher BSFC for higher biodiesel values in fuel blend. In the most reported studies the using of biodiesel has increased the BSFC of the engine. The most important parameter which may decrease the BSFC of the engine while using biodiesel is its LHV. The decrease of the BSFC while using of the biodiesel in this study may be due to its higher LHV. But there is some studies which shows a slight decrease in BSFC (Buyukkaya, 2010).

3.1.3 Exhaust gas temperature

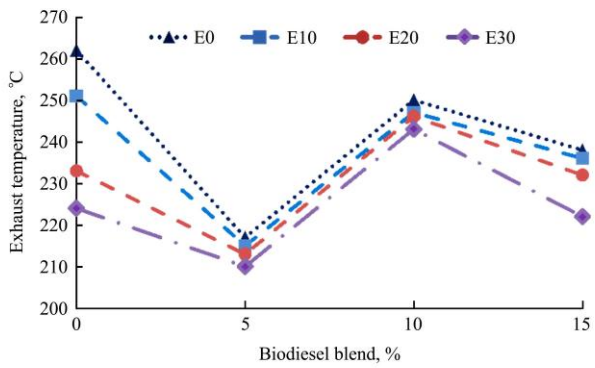
The values of the exhaust gas temperature in different engine load and EGR rate for 1800 rpm engine speed and B15 fuel blend is shown in the Figure 5a. The exhaust gas temperature increased with increase in engine load in all engine speed. This is due to higher released energy in the cylinder, which comes from higher mass of burned fuel in the cylinder. In addition the increase of exhaust gas temperature determined by the increase of load is higher than that determined by the increase of engine speed. The exhaust gas temperature has been decreased with increased in EGR rate. The value of the exhaust gas for all of the EGR rates is lower than that in the zero EGR rate. Same trend has been reported by other researchers (Mani et al., 2010).

The increase of the biodiesel percent of the fuel blend increases the exhaust gas temperature. This can be seen in the Figure 5b. In this figure effect of the Biodiesel and EGR rate on the exhaust gas temperature in 1800 rpm engine speed and 75 engine load has been shown. As it can be seen the exhaust gas temperature has been decreased for B5 fuel blend then increased for B10 and finally decreased for B15. Generally, different effects of biodiesel on exhaust gas temperature have been reported. Some works describe an increase of exhaust gas temperature due to the biodiesel utilization (Agarwal and Agarwal, 2007; Gokalp et al., 2011); on the contrary, some other works describe the opposite (Rakopoulos et al., 2014).

The characteristics of biodiesel effective on exhaust gas temperature are: viscosity, density, lower heating value (LHV) and oxygen content (Chauhan et al., 2012; Rakopoulos et al., 2014; Usta, 2005). The poor and incomplete combustion due to the higher density and viscosity of the biodiesel has been reported as a reason for the higher exhaust gas temperature of biodiesel blend fuel content (Chauhan et al., 2012; Rakopoulos et al., 2014; Usta, 2005). Reduction in exhaust gas temperature is a signal of decrease in engine losses. As it can be seen, the engine power while fueled by fuel blends which had a lower engine losses or exhaust gas temperature were higher than those with higher exhaust gas temperature (Aliyu et al., 2011; Hebbal et al., 2006). So, the reduction of exhaust gas temperature due to using of biodiesel is an advantage of this fuel (Usta, 2005). In addition, it is proved that the ignition delay of biodiesel is shorter than the diesel fuel and this also can be one of the reasons to reduction of exhaust gas temperature. Thus, shorter ignition delay shows that the combustion is started and ended in sooner than diesel fuel. This may provide a time to cooling down the exhaust gas temperature. The increase in exhaust gas temperature while using biodiesel fuel may come from its higher viscosity (Chauhan et al., 2012).



a. Effect of engine load (%) and EGR rate (%) on engine exhaust gas temperature (℃) in 1800 rpm engine speed and B15



b. Right: Effect of biodiesel (%) and EGR rate (%) on engine exhaust gas temperature (g kW h^{-1}) in 1800 engine speed and 75% engine load

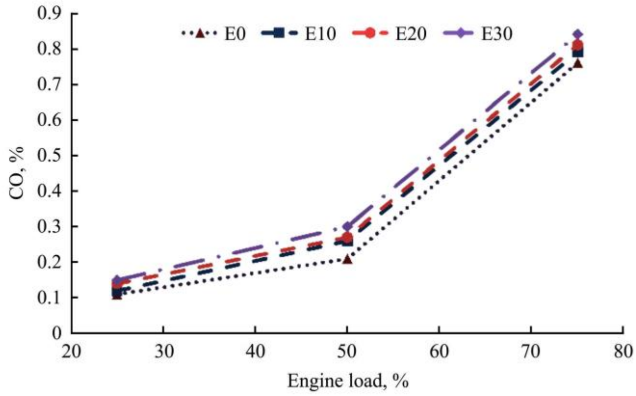
Figure 5 Effect of engine load and EGR rate on engine exhaust gas temperature

3.2 Emissions

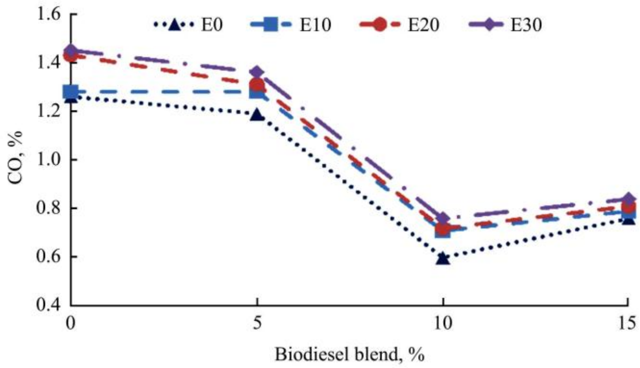
3.2.1 CO

One of the products of incomplete combustion in the engine cylinder is CO (Carbon monoxide) (Nalgundwar et al., 2016). In all engine speed the CO emission of the all biodiesel diesel blends is lower than that in diesel fuel (Figure 6). This decrease is due to the oxygen content of the biodiesel (Gumus and Kasifoglu, 2010). This additional oxygen help to make more complete combustion and hence lower production of the CO emission (Sanjid et al., 2016). It was observed that the CO emission decreased with the increase in engine speed and increased with increase in engine load. The highest CO emission reduction of 52.38% was measured for B10 fuel at 1800 rpm and 75 engine load. There are several variables acting on the combustion process that has an impact on CO formation. The additional Oxygen present in the biodiesel will assist in making the combustion more complete in the combustion zone but at the high load condition the higher viscosity of the biodiesel could affect the fuel injection and atomization characteristics could adversely impact on the CO emission value as the injector was optimized for Diesel fuel. The increased in-cylinder temperatures at high load would have a greater impact on the CO production of diesel fuel due to the enhanced atomization and mixing this produces. Modifications to the fuel injection system may improve the atomization characteristics of the biodiesel and hence improve the combustion at high load (Aliyu et al., 2011).

In addition, the CO emission has been increased with increase in the EGR rate. Same trend has been reported by the other researchers (Feng et al., 2013). This is due to the reduction of the temperature and oxygen availability inside the cylinder and lower homogeneity in fuel air mixture while using of the EGR. All of these parameters would decrease the combustion quality and hence increase the amount of the CO emission. In other hand, the addition of the biodiesel to the diesel fuel has been decreased the CO emission of the engine so that the amount of the CO while using B15 fuel blend the CO emission has been decreased, even in 30% EGR rate. The average reduction in CO emission in low, medium and high engine load have been 4.04%, 12.00% and 1.73%. As it can be seen in high engine load the amount of reduction of the biodiesel is lowest. In addition the highest average value is medium load. It can be due to the optimum point of the engine working. The reduction of the CO emission in low and high engine speeds where 23.35% and 8.09%, respectively. In medium engine speed the CO values has been increased. Totally, the simultaneous usage of the EGR and biodiesel has been reduced the CO emission of the engine.



a. Effect of engine load (%) and EGR rate (%) on CO emission (%) in 1800 rpm engine speed and B15



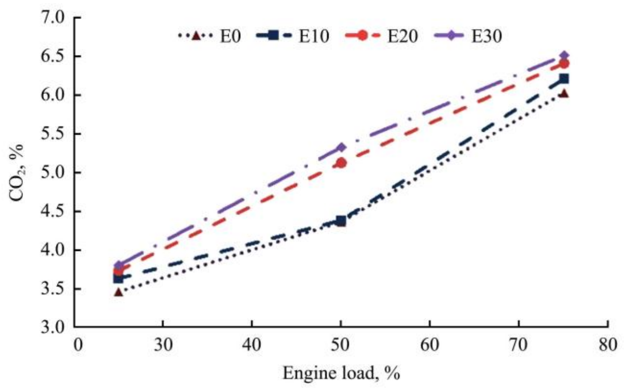
b. Effect of biodiesel (%) and EGR rate (%) on CO emission (%) in 1800 engine speed and 75% engine load

Figure 6 Effect of engine load and EGR rate on CO emission

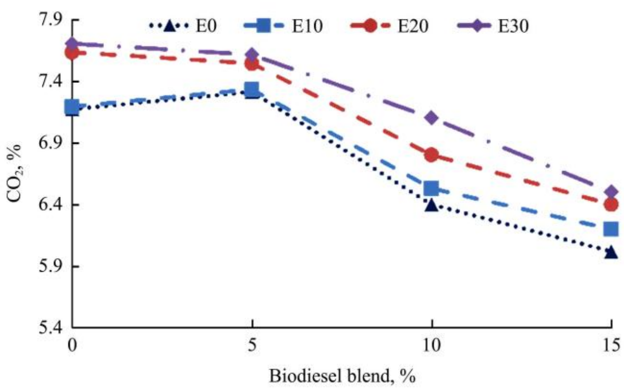
3.2.2 CO_2

This emission can contribute to serious public health problems (Rice, 2014) and also is one of the greenhouse gases which contribute in ozone formation and global warming (Gillett et al., 2013). In other hand, the increase in this emission is a signal of the complete combustion.

Figure 7a, shows the effect of the engine load and EGR rate on the CO_2 emission for 1800 rpm engine speed and B15 fuel blend. As it can be seen in this Figure 7a, CO_2 has been increased with increase in engine load and EGR rate. The CO_2 emission of all fuels has the tendency to increase with increases in engine speed for fueling with all percent of diesel biodiesel blends fuels. The CO_2 emission has been decreased for medium and high engine load while in contrary in low engine load it has been increased. But these variations in CO_2 were not significant (1.43%, –3.22% and –1.89%, respectively). The CO_2 is lower when engine fueled by diesel biodiesel blend than fueling by standard diesel in lower engine speed (Figure 7b). As can be seen in the Figure, the best percent of diesel bio diesel blend in term of the CO_2 was B15 and B20. This may be a consequence of lower viscosity of biodiesel (Silitonga et al., 2013).



a. Effect of engine load (%) and EGR rate (%) on CO_2 emission (%) in 1800 rpm engine speed and B15



b. Effect of biodiesel (%) and EGR rate (%) on CO_2 emission (%) in 1800 engine speed and 75% engine load (%)

Figure 7 Effect of engine load and EGR rate on CO_2 emission

There are some different reports in various studies about effect of biodiesel on engine CO_2 emission. Some researchers stated that the biodiesel cause increase in CO_2 emission (Ūzener et al., 2014) and the other reported an decrease in CO_2 emission when using diesel biodiesel blend instead standard diesel in engine (Gumus and Kasifoglu, 2010). In addition, the emitted CO_2 of the engine can be captured by the plant during the process of photosynthesis, while preparing seed for biodiesel (Li et al., 2009).

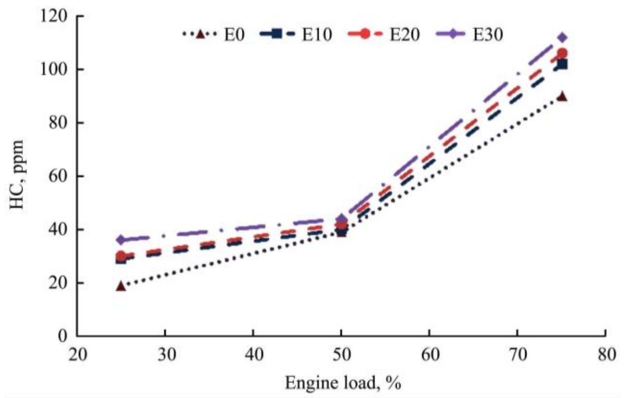
3.2.3 HC

As it can be seen in the Figure 8, the HC emission has been increased with increased in the engine load. There is same trend for all engine speed but the HC emission amount is higher for higher engine speeds. HC emission has been increased with increase in engine speed. In addition the HC emission has been increased with increase in the EGR rate.

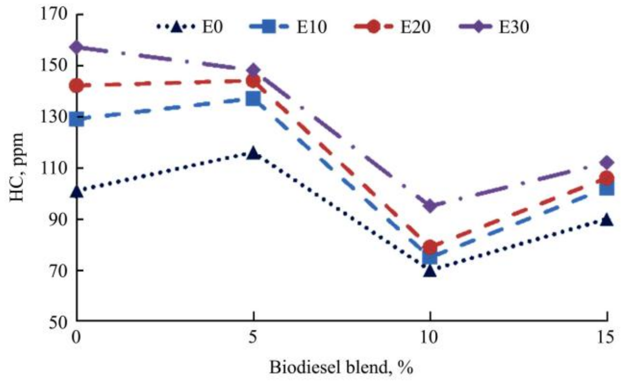
As can be seen in the Figure 8b by increasing of the biodiesel in the diesel biodiesel blends the values of the HC emission had been decreased up to B10. This graph shows the amount of HC emission in different biodiesel blend percent and EGR rate. As it can be seen in this Figure, the HC emission has been increased with increased in EGR rate, too. In addition the increased HC emission while using of the EGR reduced the cylinder oxygen and poor quality of the combustion (Mani et al., 2010; Saleh, 2009).

Generally, it can be stated that by increasing in biodiesel percent in diesel biodiesel blend, up to 10 percent the oxygen content has assisted to improve the quality of combustion. But higher percent of biodiesel cause the reduction of combustion quality due to its higher density and viscosity which alter the injection quality and reduced the homogeneity of the spray. The same result is reported for other biofuels and the oxygen content of the fuel has been introduced as the reason for this (Aliyu et al., 2011).

Using of the EGR has been increased the amount of the engine HC emission. The most interesting behavior of the HC emission while using of the EGR and biodiesel simultaneously, has been the reduction of this emission. The oxygen content of the biodiesel has been decreased the HC emission of the engine and it compensate the increase of this emission due to using of the EGR (Saleh, 2009).The highest reduction in HC emission is for B10 fuel and 0% EGR and it was 34.10 percent. The HC emission has been increased in low engine load (1.43%) and decreased in medium and high engine load (3.22% and 1.89%). As it can be seen the variation of the HC while using of the biodiesel and EGR simultaneously, is not significant.



a. Effect of engine load (%) and EGR rate (%) on HC emission (%) in 1800 rpm engine speed and B15



b. Effect of biodiesel (%) and EGR rate (%) on HC emission (%) in 1800 engine speed and 75% engine load

Figure 8 Effect of engine load and EGR rate on HC emission

3.2.4 NO_x VS. Smoke

The NO_x emission of the CI engine may be the most important emission of this type of the engine. This comes from lean combustion and high temperature in the CI combustion (Verschaeren et al., 2014). There are two main mechanisms to formation of the NO_x in the CI engine (Masum et al., 2013):

- Zeldovich mechanism

Generally, the formation of the NO_x through this mechanism required sufficient oxygen and residual time of the combustion blend, high temperature and nitrogen availability. In the Equations (2)-(4) show this mechanism.

$$N_2+O_2 \leftrightharpoons NO+N \tag{2}$$

$$N+O_2 \leftrightharpoons NO+O \tag{3}$$

$$N+OH \leftrightharpoons NO+H \tag{4}$$

- Fennimore mechanism

This mechanism is responsible to formation of the NO_x in lower temperature combustion, reach air fuel blends and short residual time. One important aspect of this mechanism is its higher dependency to the chemical composition of the fuel than Zeldovich mechanism. This is due to presence of the hydrocarbon in the reaction of the Fennimore mechanism.

$$CH+N_2 \leftrightharpoons HCN+N \tag{5}$$

$$CH2+N_2 \leftrightharpoons HCN+NH \tag{6}$$

$$N+O_2 \leftrightharpoons NO+O \tag{7}$$

$$HCN+OH \leftrightharpoons CN+H_2O \tag{8}$$

$$CN+O_2 \leftrightharpoons NO+CO \tag{9}$$

The variation of the NO_x in different test condition is shown in the Figure 9. As it can be seen in this Figure, the NO_x emission has been increased with increase in lower engine speed but with further increase in the engine speed the amount of the NO_x has been decreased. In addition in lower engine speed the values of the NO_x emission increased with increase in biodiesel percent in the blend. The NO_x emission has been decreased with increase in EGR ratio (Figure 9 and Figure 10).

Totally, addition of the biodiesel to the diesel fuel has been decreased the NO_x emission of the engine for B10 and B15. The highest increase in the NO_x emission is for B5 fuel blend. The value of the NO_x emission has been increased 39.57% than that in B0 fuel. But by using of the EGR the amount of this emission has been increased just 12.95% for B10 fuel blend. So, it can be stated that by using of the EGR the increase in the NO_x emission of the engine due to using biodiesel can be reduced. The average of the reduction in the NO_x emission for low, medium and high engine loads have been (25%, 50% and 75% engine load) 8.73%, 15.34% and 5.72%, accordingly. As it can be seen in medium engine loads the value of the reduction of the NO_x emission has been higher than low and high engine loads. The trends of reduction of the NO_x emission for low, medium and high engine speeds are as same as the loads. The NO_x emission has been decreased as 3.68%, 21.25% and 7.29% for low, medium and high engine speeds.

The variations of smoke emission in different engine test have been shown in the Figure 9 and Figure 10. As can be seen in this figure, using of the lowest value of the biodiesel (B5) has not a significant effect on smoke or has increased slightly the smoke. The smoke emission has been decreased for B10 and B15. Formation of the smoke is the result of the incomplete combustion of the liquid fuel and partially reacted of carbon of the fuel hydrocarbon (Ūzener et al., 2014). The reduction of the smoke emission while using of the biodiesel is due to its oxygen content (Wang et al., 2016) and also reduction of the carbon in the molecular structure of the biodiesel than diesel fuel (Ūzener et al., 2014).

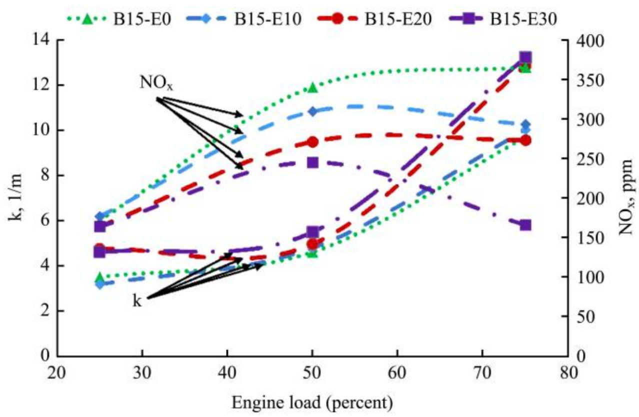


Figure 9 Effect of EGR rate on NO_x and smoke at different engine loads (2100 rpm engine speed and B15 fuel blend)

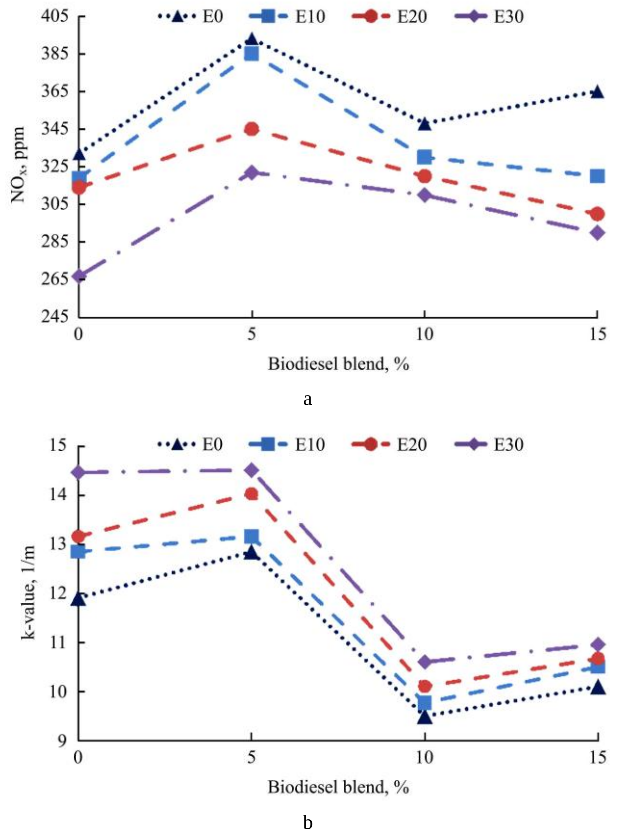


Figure 10 Effect of biodiesel (%) and EGR rate (%) on (a) NOx emission and (b) smoke (%), in 1800 engine speed and 75% engine load

Using of the EGR has been decreased the combustion temperature due to the decrease and dilution of the oxygen content with increase of specific heat capacity of the in-cylinder charge. The decrease in the temperature of the combustion and lower oxygen content with EGR cause a rising in the formation rate of carbon nuclei from unsaturated smoke forerunners such as acetylene and ethylene and decrease in the smoke oxidation level (Can et al., 2016).

The highest increase in smoke emission due to using EGR was for B10-E30-25%-1800 rpm (36.87%). In lower engine load, increase of the smoke emission due to EGR is more than that in medium and high engine load. This may be due to the oxygen content, lower aromatic and sulfur contents of biodiesel fuel (Can et al., 2016). The smoke emission of the engine has been increased with increase in the EGR rate. In other hand, this emission has been decreased while increase in biodiesel in the diesel biodiesel fuel blend. Without using of the EGR (EGR rate = 0%), the smoke emission of the engine for the B5, B10 and B15 has been decreased as 33.33%, 42.63% and 35.26% than that in B0 fuel blend in 1800 rpm, respectively. Generally it is noticeable that the total amount of the smoke emission while simultaneously using of the EGR and biodiesel has been decreased. The smoke emission in low load has been decreased (3.79%) and also for medium and high engine speed has been decreased (7.22% and 0.67%).

In the Figure 9, effect of the different EGR rate on the amount of the NO_x and smoke emission for B15 fuel blend and 1800 rpm engine speeds in all engine loads is shown. As can be seen in this figure reduction of the NO_x emission by using of the EGR has a penalty and it is the increase of the smoke emission. But by using of the biodiesel and due to its specific characteristics like oxygen content, the increase in the smoke emission for lower values of the biodiesel diesel blends has not increased significantly.

4 Conclusion

In the present study effect of using of different blends of biodiesel and EGR rate on the performance and emission of a single cylinder CI engine has been investigated. According to the results of the study, following conclusions can be drawn:

1) The value of the NO_x emission has been increased with increase in the biodiesel in diesel biodiesel blend

and decreased with increase in EGR rate. Effect of the EGR to reduction of the NO_x emission in the higher value of the biodiesel (B15) has been lower. The highest reduction of the NO_x emission has been for the B5 biodiesel diesel blend.

2) The smoke emission of the engine has been decreased for B5 and increased for B10 and B15 fuel blends. The smoke emission has been increased with increase in the EGR rate especially in higher value of the biodiesel.

3) Co and HC emissions has been decreased for B5 and B10 biodiesel but with increase of the biodiesel to B15 increased. In addition, increase in the amount of the EGR rate has been increased these two emissions and this increase has been higher for B15 fuel blend.

4) BSFC of the engine has been decreased for B5 fuel and increased for the B10 and B15 fuel blends. The EGR has been increased the BSFC of the engine. The increase of the BSFC due to using of the EGR can be seen more clearly n the B15 fuel blend.

5) Engine power for B5 fuel blends is approximately same as the B0 but for B10 and B15 the engine power initially increased then has been reduced. The EGR has been decreased the engine power especially in the lower engine load.

6) For all operating conditions, a better trade-off between HC, CO and NO_x emissions can be attained within a limited EGR rate of 10%-20% with little economy penalty.

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Nomenclatures:

Abbreviation	Meaning
BSFC	Brake specific fuel consumption (gr kWh^{-1})
CI	Compression ignition
EGR	Exhaust gas recirculation
CO	Carbon mono oxide
CO_2	Carbon dioxide
HC	Hydrocarbon
LVH	Lower heating value
NOx	Nitrogen oxides
BX	X percent biodiesel in blend with diesel