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Performance and Emission Analysis of a DI Diesel Engine Fueled with Blends of Ethanol and Methanol in Biodiesel-Diesel-EHN using EGR

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ABSTRACT
This study investigates the performance (BTE and BSEC) and emissions (CO, HC, NOx and smoke) of biodiesel-diesel blends of B20, B50 and B100 mixed with methanol and ethanol at 5% and 10% v/v, and 1% 2-ethylhexyl nitrate (EHN). The blends were tested under two conditions (without EGR and with EGR), on a twin-cylinder HATZ 2G40 light-duty direct injection (DI) diesel engine at 3000 rpm at different load conditions (low load: 20%, medium load: 50%, and high load: 80%). Although methanol and ethanol helped reduce the biodiesel's viscosity, increasing the amount of methanol and ethanol also decreased the biodiesel's cetane number (CN). Therefore, to overcome this issue, the use of an additive EHN was used as a CN improver to reduce ignition delay and soot formation. The performance and emission results with blends of ethanol and methanol in biodiesel-diesel-EHN were compared to that of base fuels (B0, B20, B50 and B100).

Keywords: 2-ethylhexyl nitrate, ethanol, exhaust gas recirculation, methanol, modern small diesel engine.

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I. INTRODUCTION

Diesel engines are the main choice of transportation, agriculture machinery, and mining equipment because of their higher thermal efficiency. Diesel engine manufacturers face a major challenge of improving the efficiency of engines without increasing the amount of pollutants that diesel engines contribute to the environment. In 2010, there were 700 million vehicles on the road including heavy-duty trucks, light-duty vehicles, automobiles, SUVs and light trucks, which will increase to 1.3 billion by 2030. This is an alarming indication of the fact that the level of air pollution will also increase due to the emission from these fuels, which has been the main concern. The increasing pollutants (i.e., HC, CO and NOx from diesel engines) are the major cause of environmental hazards such as ozone depletion, acidification and global warming. The above concerns have encouraged researchers to pursue alternative fuels to decrease environmental hazards from emissions, and to increase engine efficiency.

The increasing concern of depleting fossil fuels and their effects on the environment have inspired biofuel research. Biofuels such as biodiesel, which has gained popularity in last few decades, is the future [1,2]. Various types of alcohol, such as ethanol, were also used as a direct engine fuel [3].

Biodiesel can be easily produced through different processes such as transesterification from different kinds of fats and vegetable oils. As reported, Canada permitted the use of 2% biodiesel-in-diesel fuel in 2012, with a further 5% increase in 2015. Furthermore, in terms of production, biodiesel production rose from 14.7 billion gallons to nearly 26 billion gallons from 2009 to 2015 [4]. The major concern that has haunted researchers is the rate at which fossil fuels are depleting. The US Energy Information Administration has estimated that the world's fuel consumption will increase from 86.1 million barrels/day to 110.6 million barrels/day by 2035 [5,6].

Biodiesel can be used directly as engine fuel without any engine modifications. Pure biodiesel and biodiesel-diesel blends reduce the levels of HC, smoke density and CO, but at the cost of increasing NOx [7]. NOx is the major cause of smog, acid rain and ground level ozone [8]. Although biodiesel has higher viscosity, pour point, lower volatility and poor cold flow property, research has proven that including methanol and ethanol in diesel-biodiesel blends can improve the cold flow property and PM emissions. However, adding these two as additives lowers the CN of biodiesel, which further leads to ignition delay and delay in combustion, resulting in higher emissions [9]. A study was conducted by Orkun et al. on the combustion, performance and emission of a diesel engine fueled with biodiesel produced from soybean oil and its blends (SB10, SB20, and SB50). The engine speed ranged from 1200 rpm to 3000 rpm. They concluded that biodiesel reduced CO by approximately 28-46%, but NOx increased about 7-18% compared to diesel [10]. Biodiesel has a higher CN, and contains 10-12% more oxygen than diesel by weight [11]. Research conducted by Wu et al. concluded that PM emissions can be reduced by 53-69% when a Cummins ISBe6 DI engine with a turbocharger and intercooler is fueled with five pure biodiesels [12]. Krahn et al. saw a CO reduction of nearly 50% when biodiesel was produced from rapeseed oil compared to low and ultra-low sulfur diesel [13].

The use of additives such as methanol helps in complete combustion of biodiesel, which has 30% higher oxygen in comparison to diesel. Furthermore, the addition of alcohol helps reduce HC and CO emissions [14,15]. Zhu et al. studied blends of pure biodiesel and biodiesel combined with 5%, 10% and 15% ethanol and methanol on a 4-cylinder DI engine under five engine loads at 1800 rpm, and observed an increase in BTE for the 5% blended fuels of methanol and ethanol [16]. On the other hand, using alcohol-diesel blends has many disadvantages: decreased lubricity, viscosity, CN, and ignitability [17]. Various studies show that NOx emissions decreased when the engine was fueled with jatropha oil-methanol, with a decrease in NOx and CO when 20% ethanol was blended with biodiesel in a diesel engine [18,19].

EHN is a widely used additive to avoid ignition delay in a diesel engine. Li Ruina et al. found that adding EHN to diesel increased the CN by 4% [20]. When 0.3% EHN was added to a blend of 90% biodiesel-10% methanol, NOx emissions and smoke were reduced. Erol and Günnur discovered that out of four antioxidants (TBHQ, BHA, BHT and EHN), EHN was the best antioxidant to reduce NOx emission [7]. In a study conducted by Roy et al., adding 5% ethanol to B20, B50 and B100 generated lower CO, NOx and HC emissions compared to B0 when biodiesel was produced from canola oil through the transesterification process [21]. Nadir Yilmaz concluded that when methanol and ethanol were used in a ratio of 10% and 20% in the B50 blend, CO and HC were reduced more with methanol-B50 blends, but reduction in NOx was noticed in ethanol-B50 blends [22]. Other studies of B100 blends showed that the addition of methanol and ethanol increased HC and CO. Adding 15% methanol in B100 increased more HC and CO than 15% ethanol in B100 [23]. B20-EHN blends were neutral compared to B0 in terms of emissions [24]. In a comparative study carried out by M. Vijay Kumar et al., EHN was found to be the best antioxidant in reducing ignition delay, to boost the CN, and to reduce engine noise while improving cold weather conditions compared to DTBP [25]. Another study showed that 2% and 5% canola oil mixed with pure diesel in diesel engine helped reduce NOx by about 10-15% at 20% EGR at 2100 rpm [26].

The presence of EHN enhanced the combustion rate for all the blends, and the presence of methanol made the blend leaner, which resulted in increased BTE [27,28]. An analysis conducted by Sharp followed the old trend, which showed that when 0.5% EHN is mixed with B20 in a DI engine, the CO emission is barely affected [29]. A combined research concluded that biodiesel and its blends produced fewer emissions than B0. However, the addition of either oxygenated additives such as alcohol, or cetane booster additives such as EHN, increased biodiesel's HC and its blends compared to B0 [30].

In this research, the new trend which is followed is that we combined the advantages of the biodiesel- alcohol blends (methanol and ethanol) and biodiesel-EHN. In total, sixteen blends were tested under the conditions of without and with EGR.

The EGR phenomenon is known to reduce the engine's interior temperature resulting in fewer NOx emissions. The aim of this study is to reduce the targeted emissions (i.e., CO, HC and NOx), which is why a vast variety of blends were tested.

II. MATERIALS & EXPERIMENTAL PROCEDURE

2.1 Material Used and Biodiesel Production

The petroleum diesel used in the experiment was purchased from a local gas station, and the canola oil used for biodiesel production was purchased from a local supermarket. Methanol (100% purity), ethanol (100% purity), sodium hydroxide (99% purity) and EHN (99.5% purity) were provided by the chemical engineering lab at Lakehead University. Table 1 shows the properties of the fuels, blends and additives. The biodiesel was produced through the process of transesterification of canola oil in the presence of methanol as a catalyst, which produced biodiesel and glycerol (by-product) [31] [32]. Figure 1 depicts the production of biodiesel.

2.2 Engine Used

Table 1: Properties of fuel blends

Fuels	Composition	Heating value (MJ/kg)	Density(kg/m^3)	Viscosity (cSt@40°C)
B0	Pure Diesel	45.395	835	3.19
B20	20% Biodiesel in Diesel	43.758	842	3.54
B50	50% Biodiesel in Diesel	42.157	853	4.10
B100	Pure Biodiesel	38.758	881	4.24
Ethanol (E)	Pure ethanol	26.700	775	1.09
Methanol (M)	Pure methanol	19.900	773	0.50
EHN	2-Ethylhexyl Nitrate	15.780	933	1.73
B0M5EHN1	5% Methanol and 1% EHN in B0	43.820	833	1.83
B0M10EHN1	10% Methanol and 1% EHN in B0	42.540	830	1.76
B20M5EHN1	5% Methanol and 1% EHN in B20	42.280	839	2.43
B20M10EHN1	10% Methanol and 1% EHN in B20	41.090	836	2.33
B50M5EHN1	5% Methanol and 1% EHN in B50	40.780	850	3.00
B50M10EHN1	10% Methanol and 1% EHN in B50	39.668	846	2.87
B100M5EHN1	5% Methanol and 1% EHN in B100	37.585	876	4.03
B100M10EHN1	10% Methanol and 1% EHN in B100	36.642	871	3.84
B0E5EHN1	5% Ethanol and 1% EHN in B0	44.164	833	1.86
B0E10EHN1	10% Ethanol and 1% EHN in B0	43.229	830	1.82
B20E5EHN1	5% Ethanol and 1% EHN in B20	42.625	840	2.46
B20E10EHN1	10% Ethanol and 1% EHN in B20	41.772	836	2.39
B50E5EHN1	5% Ethanol and 1% EHN in B50	41.120	850	3.03
B50E10EHN1	10% Ethanol and 1% EHN in B50	40.348	846	2.93
B100E5EHN1	5% Ethanol and 1% EHN in B100	37.925	876	4.06
B100E10EHN1	10% Ethanol and 1% EHN in B100	37.322	871	3.90

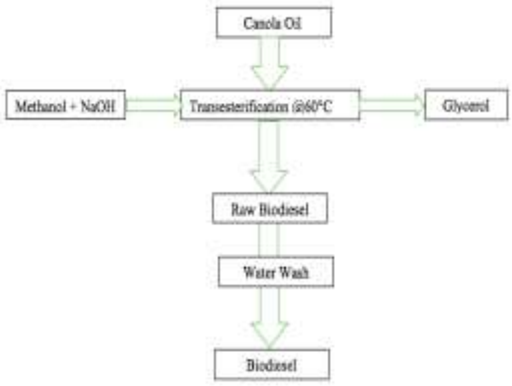


Fig. 1: Production of biodiesel through transesterification process from canola oil

Table 2: Engine specifications

Engine make & model	HATZ 2G40
Engine Type	4-stroke, air cooled
Number of cylinders	2
Bore/stroke	92 mm/75 mm
Displacement	997 cc
Compression ratio	20.5:1
Fuel injection timing	8°BTDC (≤2250 rpm); 10°BTDC (≤2300 rpm)
Fuel injection pressure	26 MPa
Continuous maximum rated power	13.7 kW @ 3000rpm
Maximum rated power	17 kW @ 3600rpm

2.3 Experimental Procedure

Figure 2 shows the experimental setup. The engine was coupled with a water-brake dynamometer and the engine was tested at 3000 rpm, where the maximum power was developed. The load conditions were low load: 20%, medium load: 50%, and high load: 80% and the loads were measured and controlled by the dynamometer. The tests were conducted without and with EGR conditions. The engine was warmed up with B0 for 30 minutes before conducting the experiments, and the tested blends were subsequently supplied. The brake power, fuel consumption and engine load were measured to further calculate the engine's BSEC and BTE.

To measure the emissions (O_2, CO and CO_2 in percentage, and NO, NO_2 and HC in ppm), a multi gas analyzer named NOVA Model 7466 PK was utilized. Lastly, a Smart 1500 smoke opacity analyzer was used to measure smoke. The analyzer specifications are shown in Table 3.

2.4 Exhaust Gas Recirculation (EGR) System

The EGR is defined as the system to reduce NOx emissions from a gasoline or diesel engine. The way EGR technique works is by recirculating the exhaust gas from engine back to cylinders of engine which dilutes the oxygen in the intake air stream. Also, provides gases intake to combustion which act as absorbents of combustion heat which further reduces cylinder peak temperatures. Figure 3 shows the EGR system used and 15% EGR was used in this study. The formula used to calculate the percentage of EGR is

$$EGR\ \% = \frac{CO_{2(intake)} - CO_{2(ambient)}}{CO_{2(exhaust)} - CO_{2(ambient)}}$$

III. RESULTS AND DISCUSSION

The blends were tested at 3000 rpm at three operating loads (20%, 50% and 80%). The results of 3000 rpm are presented in the figures as our main focus. The analysis of the base fuels (B0, B20, B50 and B100 at 3000 rpm), are shown in Appendix Table A. The results of the fuel blends are compared to that of base fuels.

3.1 Engine Performance

3.1.1 Brake Thermal Efficiency (BTE)

Figure 4 depicts the BTE of the blends at 3000 rpm under low, medium and high load conditions. When the percentage of methanol and ethanol increased, the BTE increased. The BTE for B0M5EHN1 was 36%, which rose to 36.5% for B0M10EHN1 without EGR. A similar trend was seen for the ethanol fuel blends. The addition of methanol and ethanol attributed to higher oxygen content, which further helped improve combustion in the diesel-biodiesel blends; hence higher BTE than their base fuel blends (B0, B20, B50 and B100. Also, the addition of EHN helped reduce ignition delay, and also helped with rapid combustion. Furthermore, when the blends were tested under EGR, an increase in BTE was observed due to the increase in intake temperature, leading to a higher rate of combustion. The BTE of B0E10EHN1 without EGR was 38%, which increased to 38.5% with EGR at high load. The maximum BTE was

observed at B100E10EHN1 at high load and EGR, which is 12% more than B0 at high load and EGR.

3.1.2 Brake Specific Energy Consumption (BSEC)

Figure 5 represents the BSEC at 3000 rpm for all fuel blends. The BSEC was higher at low load because less fuel was injected into the combustion chamber, resulting in lower cylinder temperature and pressure. This resulted in less power, as well as higher energy consumption for all blends at low load. The BSEC of B20, B20M5EHN1 and B20E5EHN1 were 10.6 MJ/kWh, 11.25 MJ/kWh and 11.08 MJ/kWh, respectively, without EGR at low load. The BSEC decreased with EGR as the intake charge temperature increased, which increased the fuel's combustion rate. The BSEC decreased from 11.29 MJ/kWh (without EGR) to 8.26 MJ/kWh (with EGR) for B20M10EHN1. Adding methanol, ethanol and EHN, or increasing the percentage of methanol or ethanol in the blend increased BSEC, as these additives have low heating value, which consumed more energy. The highest BSEC was observed for B0M5EHN1 at low load without EGR, which was 14.5% higher than B0.

3.2 Emissions

3.2.1 Carbon Monoxide (CO)

Figure 6 illustrates the variation in CO emissions at low load, medium load and high load without EGR and with EGR. As the load increased, CO decreased because at low load, less fuel was injected into the combustion chamber, resulting in incomplete mixing of air and fuel, leading to incomplete combustion. CO decreased at 191 ppm, 174 ppm and 162 ppm, as well as at 184 ppm, 175 ppm and 161 ppm, as the load increased from low to medium, and then increased to high for B50 and B50M10EHN1 without EGR. An increase in CO was observed when the blends were tested with EGR due to oxygen deficiency, as observed for B50M5EHN1, which was 190 ppm without EGR,

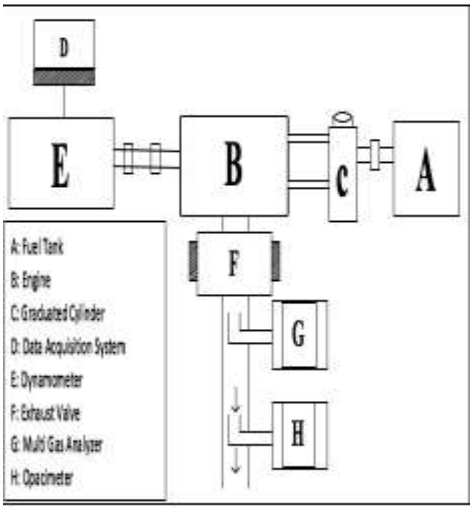


Fig. 2: Experimental setup

Table 3: Emission analyzers' specifications

Method of Detection	Species	Measured Unit	Range	Resolution	Accuracy
NovaGas 7466 PK					
Electrochemical/ Infrared detector	CO	%	0-10%	0.10%	±1%
Infrared detector	CO_2	%	0-20%	0.10%	±1%
Electrochemical	NO	ppm	0-2000 ppm	1 ppm	±2%
Electrochemical	NO_2	ppm	0-800 ppm	1 ppm	±2%
Electrochemical	O_2	%	0-25%	0.10%	±1%
Infrared detector	HC	ppm x 10	0-20000 ppm	10 ppm	±1%
Dwyer 1205A Electrochemical	CO	ppm	0-2000	1 ppm	±5%
ExTech EA10	Temp.	0.1°C	(-)200°C-1360 °C	0.1°C	±0.3%
Smart 1500	Opacity	%	0-100%	0.1%	±2%

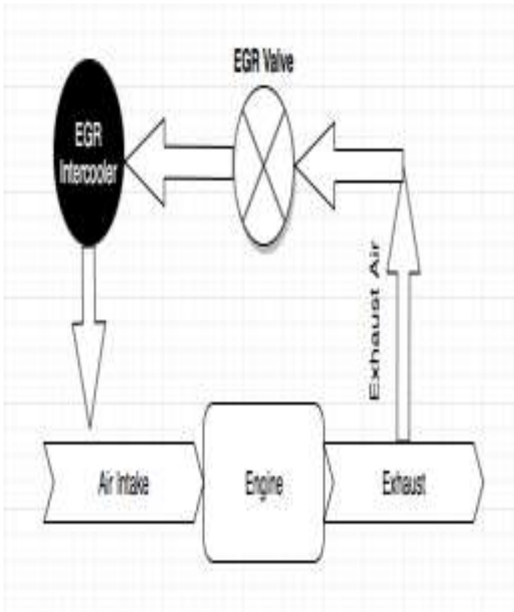


Fig. 3: EGR system

Appendix A:

Performance and Emissions of Base Fuels									
		Without EGR				With EGR			
Load	Fuel	B0	B20	B50	B100	B0	B20	B50	B100
Low Load	BTE (%)	35.2	35.7	35.9	36.5	37.0	37.4	38.1	38.5
	BSEC (MJ/kWh)	10.3	10.6	10.8	11.3	9.7	9.7	9.9	9.9
	CO (ppm)	241	219	191	149	312	283	263	229
	HC (ppm)	360	330	270	240	420	360	330	300
	NOx (ppm)	110	139	164	176	101	121	139	111
	Smoke Opacity (%)	7.2	7.3	7.4	7.6	6.1	6.3	6.5	6.9
Medium Load	BTE (%)	35.7	35.9	36.1	36.6	37.4	37.8	38.5	39.1
	BSEC (MJ/kWh)	10.1	10.5	10.8	11.3	9.6	9.6	9.9	9.7
	CO (ppm)	223	208	174	132	298	272	247	219
	HC (ppm)	330	300	240	210	390	330	300	270
	NOx (ppm)	134	159	178	198	107	139	149	163
	Smoke Opacity (%)	8.9	9.2	9.3	9.6	8.8	9.1	9.2	9.4
High Load	BTE (%)	36.0	36.2	36.2	36.8	37.7	38.1	39.0	39.6
	BSEC (MJ/kWh)	10.0	10.4	10.7	11.2	9.6	9.5	9.6	9.7
	CO (ppm)	219	199	162	121	297	269	241	210
	HC (ppm)	300	270	210	180	360	300	270	240
	NOx (ppm)	161	181	201	223	137	156	168	190
	Smoke Opacity (%)	11.2	11.4	11.6	11.8	10.2	10.4	10.7	11.0

Figure 4: BTE of different fuel blends (a) without EGR (b) with EGR

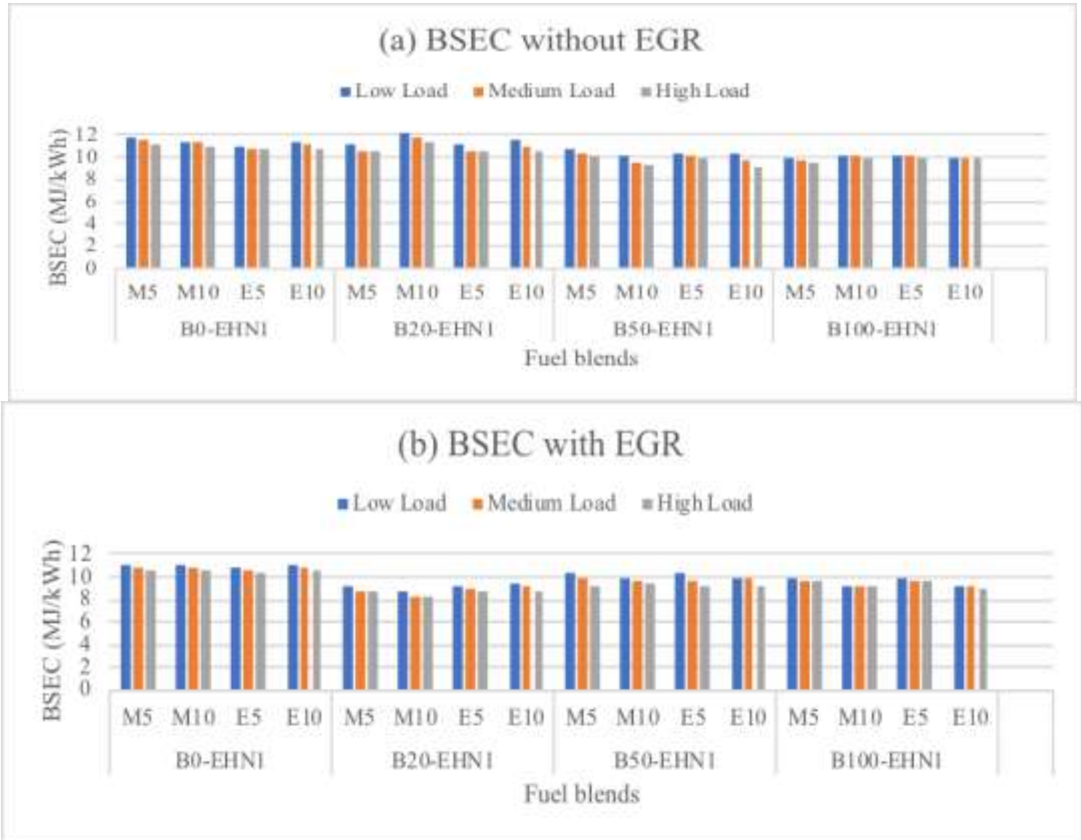


Figure 5: BSEC of different fuel blends at (a) without EGR (b) with EGR

increasing to 284 ppm with EGR. In previous studies, the increase in percentage of methanol and ethanol increased CO emissions, as the CN of both alcohols is very low. To overcome this drawback, EHN was used, which lowered CO emissions by reducing the ignition delay. CO reduced significantly to 198 ppm for B100M10EHN1 compared to B100, having 210 ppm CO at high load with EGR. The lowest CO was observed for B100M10EHN1 without EGR at high load, which was 54.5% less than B0 under the same conditions.

3.2.2 Unburnt Hydrocarbon (HC)

Figure 7 illustrates the total unburnt hydrocarbon at 3000 rpm at three load conditions. HC decreased with an increase in load, and followed the same trend as CO, as both were emissions that resulted from incomplete combustion. HC decreased from 270 ppm to 240 ppm for B100M10EHN1 at low load and high load without EGR. HC increased for all blends under EGR conditions due to oxygen deficiency, leading to incomplete combustion. The addition of methanol and ethanol increased HC emissions, as both performed a cooling effect in the blend, which reduced the combustion temperature. However, it was somehow controlled by the addition of EHN, which reduced the incomplete combustion, hence stabilizing HC emissions. HC increased from 480 ppm to 510 ppm as the methanol percentage increased from 5% to 10 % in B20EHN1 fuel blend with EGR. The maximum HC was observed for B0E5EHN1 at medium load, which was 40% higher than B0.

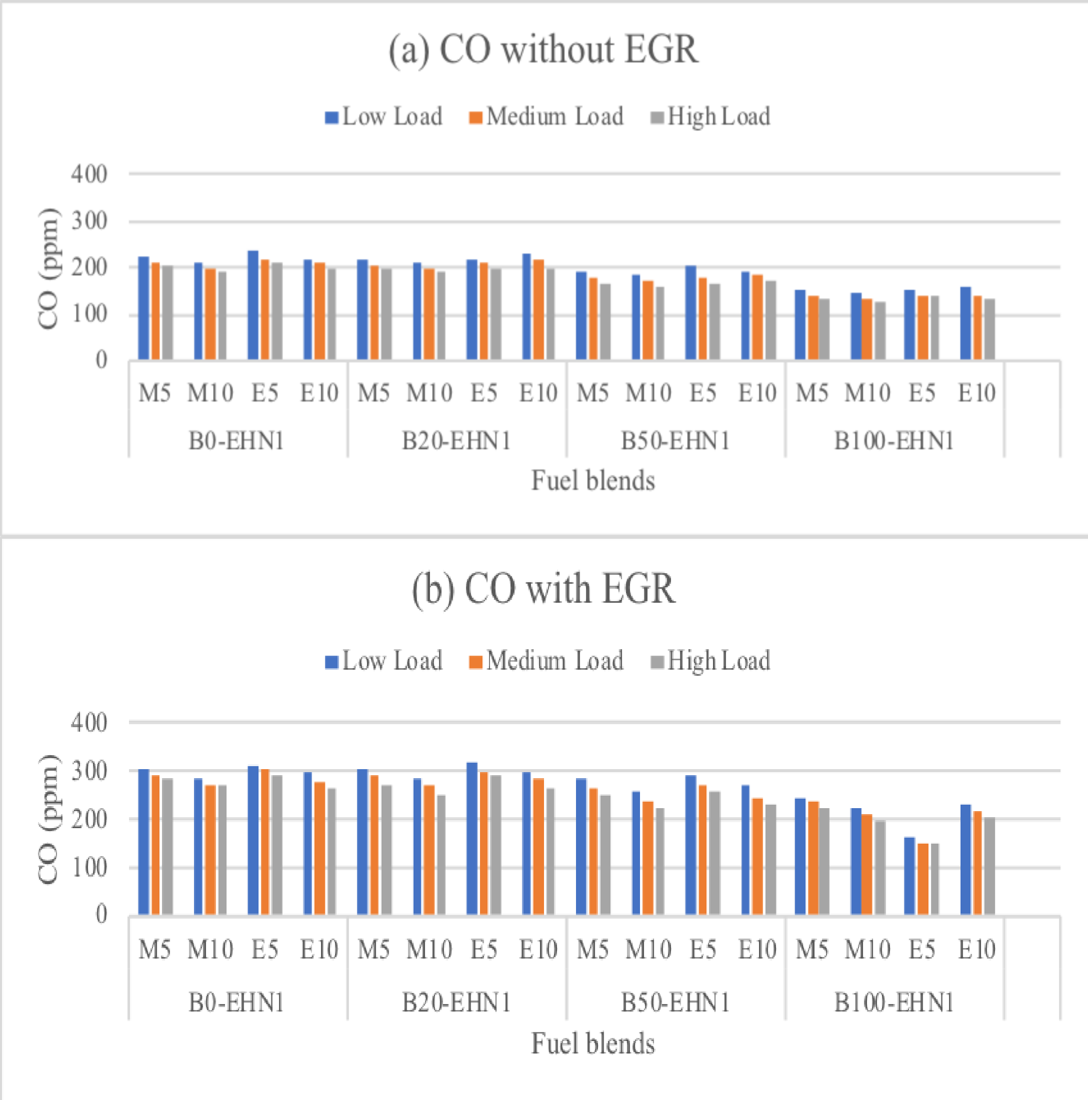


Figure 6: CO emissions of different fuel blends (a) without EGR (b) with EGR

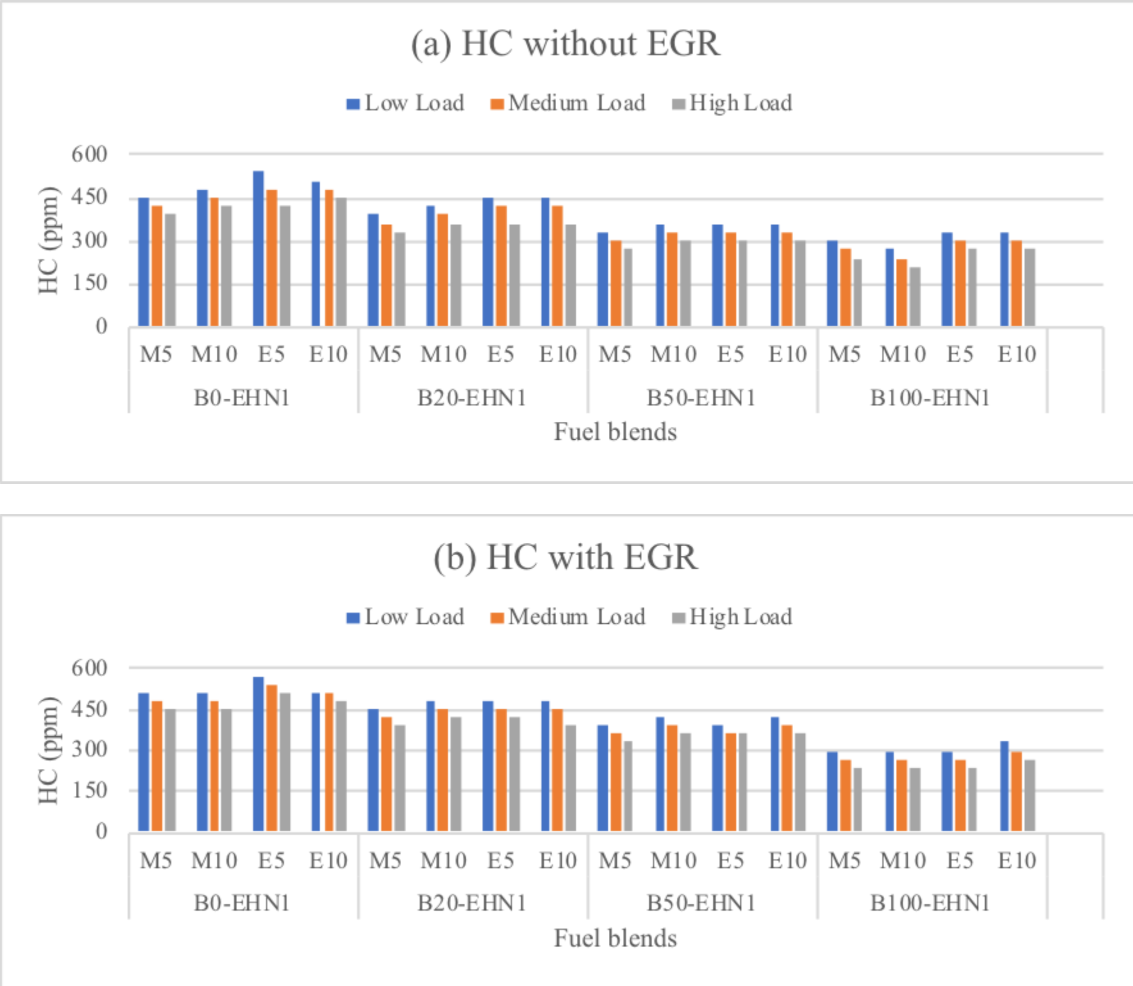


Figure 7: HC emissions of different fuel blends (a) without EGR (b) with EGR

3.2.3 Oxides of Nitrogen (NOx)

Figure 8 represents NOx emissions for all blends at 3000 rpm. As the load increased, NOx emission also increased. The increase in percentage of biodiesel also contributed to the increase in NOx [33]. The decreased NOx emissions were observed for all blends with EGR, because EGR reduces the combustion temperature, as well as oxygen content. Although EHN belongs to the nitrate group, it helps reduce NOx as it ignites the combustion process, resulting in lower NOx. NOx emissions were 190 ppm for B100, and 121 ppm for B100E10EHN1, at high load with EGR, proving that the mixture of ethanol and EHN reduced the amount of NOx when added to B100. The lowest NOx was observed for B0E10EHN1 at low load with EGR, which was 21% lower than B0.

3.2.4 Smoke

Smoke intensity for all blends is depicted in Figure 9 without and with EGR. As the load increased, smoke intensity increased 6% for B50M5EHN1 as the load increased from low to high without EGR. Biodiesel's higher viscosity contributed to increased smoke intensity. Therefore, as the percentage of biodiesel in diesel increased, smoke intensity increased by 2% in B20E10EHN1 and B100E10EHN1 without EGR. Increasing the percentage of methanol and ethanol decreased smoke due to the alcohol's high volatility, which helped improve fuel mixing. The blends showed a slight less smoke intensity with EGR due to proper fuel mixing at elevated inlet temperature. Smoke intensity was reduced from 15% without EGR to 14.5% with EGR for B100E10EHN1.

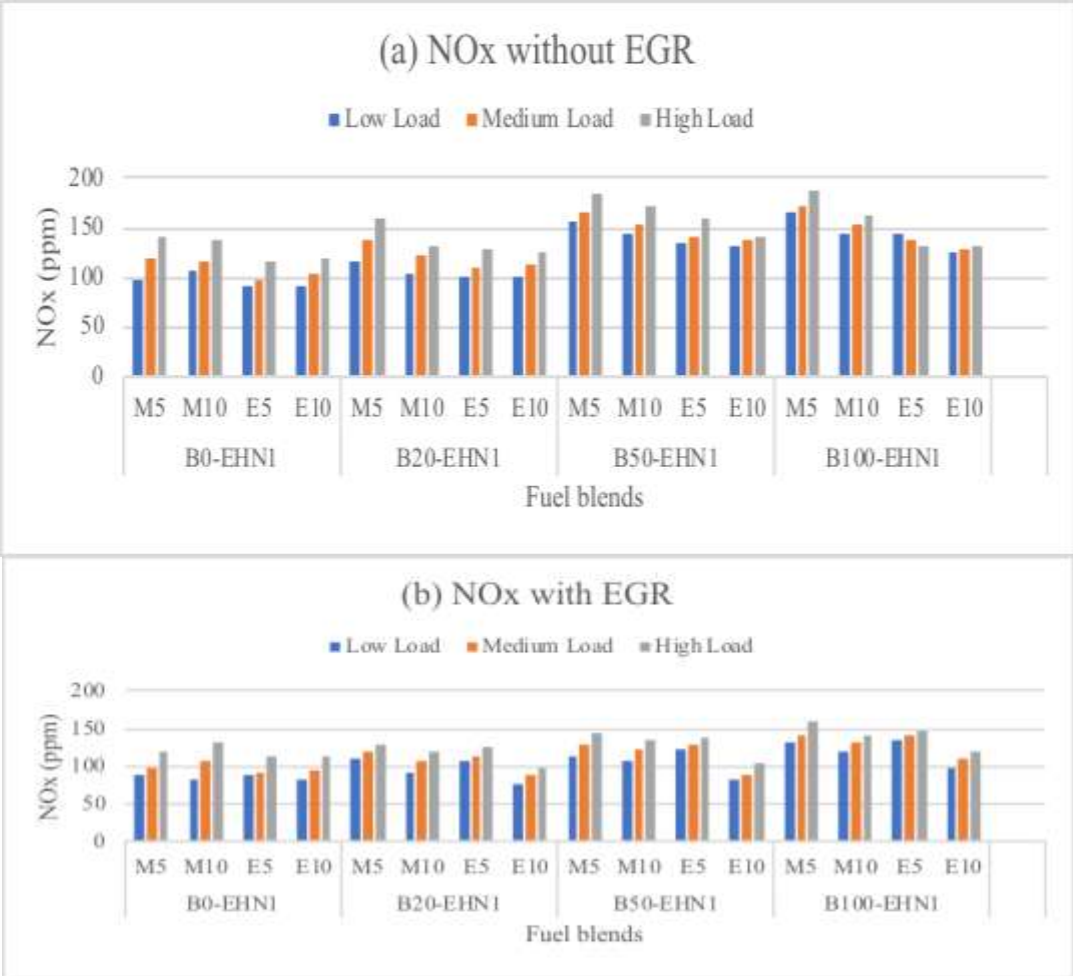
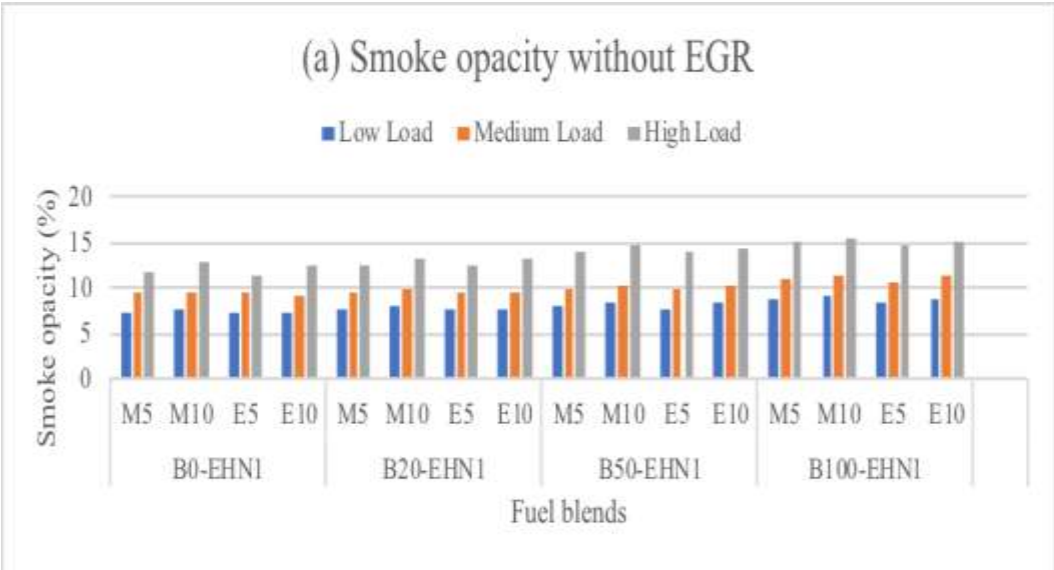


Figure 8: NOx emissions of different fuel blends (a) without EGR (b) with EGR



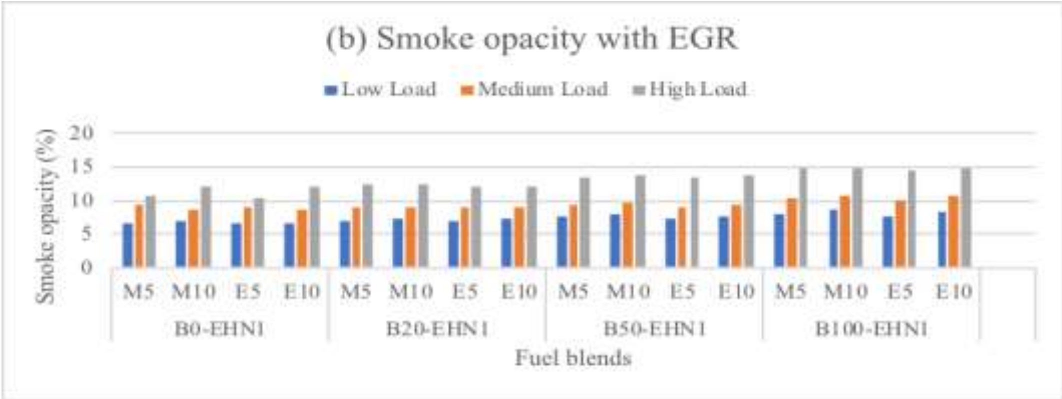


Figure 9: Smoke emissions of different fuel blends (a) without EGR (b) with EGR

IV. CONCLUSIONS

The conclusion of all results is summarized as follows:

a. EHN addition to the methanol-biodiesel-diesel and ethanol-biodiesel-diesel resulted in better fuel combustion and fewer emissions.

b. Engine performance was enhanced from the use of ternary blends. BTE increased by an average of 4% for all the blends compared to B0 without EGR. BTE for the ethanol blends was more than in the methanol blends.

c. CO increased by 4.5% in the ethanol blends compared to the methanol blends without EGR, but when the blends were tested with EGR, the methanol blends had a 1% increase over the ethanol blends. In the methanol blends, CO decreased by 19% and 12% without EGR and with EGR, respectively, than B0; in the ethanol blends, CO was reduced by 14.5% and 13.5% without and with EGR than B0.

d. HC increased by 8% and 7% for methanol blends when compared to B0 without and with EGR. In addition, for ethanol blends, the increase was 13.5% when compared to B0 without and with EGR. HC was lower for methanol blends than the ethanol blends by 8% and 10%, respectively, with and without EGR.

e. The decrease in NOx for methanol-blends was less than 2% compared to B0, but for ethanol blends, NOx reduced by 13.5% and 14% when compared to B0 with and without EGR. NOx emissions in the methanol blends were 11% and 13% higher than ethanol blends with and without EGR.

f. Smoke opacity for ethanol blends was less than methanol blends by 4% and 2.5% without and with EGR. The increase was 23% and 24% for methanol blends compared to B0, whereas the increase was 20.5% and 22% without EGR and with EGR.

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