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Evaluation of the environmental and cost impact of a small diesel engine with ethanol-diesel and isopropanol-diesel fuel at varying engine loads and speeds

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Abstract – Nowadays, alcohol additives such as ethanol and isopropanol are used to minimize emissions resulting from combustion in diesel engines. While these blends contribute to reducing emission values, it is also important to consider their environmental and cost implications. Therefore, this experimental study focuses on the emission characteristics and the environmental and cost impact of alcohol additives in diesel fuel. The experiments were conducted at low and medium engine torques (3 Nm and 6 Nm) and various engine speeds (1000, 1500, 2000, and 2500 rpm). Additionally, three different test fuels were used in the experiments, including standard diesel fuel, as well as diesel fuel with volumetric additions of 7% ethanol (E7) and 7% isopropanol (IP7) alcohol additives. The emission values of all test fuels were measured, and an analysis of environmental influence and cost was conducted. Upon examining the results, it is evident that the addition of alcohol to diesel fuel significantly increased the environmental influence and cost at low engine speeds, while it led to a decrease at high engine speeds. Furthermore, the increase in engine load contributed to emission reduction due to higher combustion temperatures, thereby contributing to a decrease in both cost and environmental influence.

Keywords – Alcohol Blends, Cost Analysis, Diesel Engine, Emissions, Environmental Impact

I. INTRODUCTION

Due to rising energy demands, and strict emissions standards, the focus on environmental preservation and energy conservation has become increasingly significant in the present era [1]. The annual escalation in vehicle quantities leads to substantial energy consumption and the release of detrimental exhaust emissions. This circumstance has adverse implications for both the environment and human well-being. Consequently, numerous developed nations have implemented zero-emission initiatives, profoundly influencing the trajectory of the automotive sector. Internal combustion engines assume a pivotal function in mitigating emissions and facilitating energy preservation [2, 3]. Therefore, nowadays, many researchers are working on the utilization of alcohol fuels to reduce emissions in compression ignition (CI) engines. Ethanol and isopropanol are among these alternative fuels.

Ethanol exhibits promising characteristics as a potential fuel due to its abundant availability from renewable bio-based sources and its inherent oxygen content, which enables the reduction of hydrocarbon (HC), carbon monoxide (CO), and particulate matter (PM) in diesel engines [4]. Ethanol is recognized as a renewable source since it can be derived from agricultural crops [5, 6]. With its high-octane content, ethanol is well-suited for use as an additive in CI engines with high compression ratios [7]. Isopropanol, with its oxygenated content, presents itself as another promising alternative fuel that can be derived from raw materials similar to ethanol. Isopropanol offers enhanced compatibility with fuel mixtures (diesel) owing to its longer chain frame when compared to other alcohol fuel (ethanol) [8]. Additionally, isopropanol exhibits slightly superior cetane number and heating value, making it an alternative option to other alcohols such as ethanol, buthanol, and methanol [8-11].

In the existing body of literature, numerous investigations have been carried out on blends of ethanol-diesel and isopropanol-diesel. Presented below is a summary of selected studies pertaining to ethanol-diesel and isopropanol-diesel blends. Huang et al. [12] conducted an analysis to examine the impact of incorporating varying percentages of ethanol (10%, 20%, 25%, and 30%) into diesel fuel on harmful emission parameters. Their findings revealed a substantial diminution in smoke opacity when ethanol was put in diesel, which can be attributed to the oxygen (O_2) content present in ethanol. However, it was noted that the desired abatement of detrimental gases, specifically HC, CO, and nitrogen oxide (NO_x) gas, could not be realized. Ahmed's study [13] specifically investigated the impact of ethanol as an additive in a heavy-duty diesel engine. The experiment results indicated a significant reduction in PM emissions by more than 40%. Furthermore, CO and NO_x emissions exhibited reductions of over 25% and 5% respectively. Xing-Cai et al. [14] conducted a study to assess the influence of a cetane improver added to ethanol-diesel mixtures on the emissions and performance of a diesel engine. Ethanol was blended with diesel at a volume ratio of 15%. The cetane improver was added at different ratios: 0%, 0.2%, and 0.4%. The results revealed that engine performance parameters showed an increase in fuel consumption and improved thermal efficiency. Notably, emissions exhibited improvements as well. Smoke and NO_x emissions experienced significant reductions as a result of the ethanol-diesel blend with the addition of the cetane improver. Zhang et al. [15] investigated the solubility of ethanol in diesel fuel and its impact on harmful gas by conducting tests with various fuel blends in a diesel engine. The volumetric composition of ethanol in the fuel mixtures comprised 10%, 20%, and 30% respectively. The study revealed a notable reduction in smoke, HC, and CO emissions with the addition of ethanol to the fuel blend. The findings demonstrated that incorporating ethanol into the diesel fuel mixture resulted in significant improvements in emission characteristics. A study was conducted by Alptekin [10] to compare the performance and detrimental emissions of diesel-isopropanol and diesel-ethanol blends in a common rail (CRDI) diesel engine, considering different speed and load conditions. Isopropanol was introduced into diesel fuel at a volume ratio of 15%. The performance test results revealed that the addition of alcohol to diesel led to a degradation in fuel consumption. Furthermore, it was reported that higher levels of HC, CO, and NO_x emissions were observed compared to conventional diesel fuel. Liu et al. [16] conducted a study to investigate the impacts of incorporating isopropanol as an additive on the performance and harmful emissions of a diesel engine under various spray timing conditions. Isopropanol was blended with diesel fuel at different substitution fractions: from 5% to 20% by volume. The test results revealed that fuel consumption worsened as the ratio of isopropanol augmentation increased under the same operating circumstance. In comparison to diesel, the utilization of isopropanol led to augmented NO_x and HC emissions. Hazar and Uyar [17] conducted a study that examined the impacts of isopropanol-diesel mixtures on performance and emissions. The isopropanol-diesel mixtures were prepared with volume ratios of 2%, 8%, 12%, and 18%. According to the paper, it was reported that the inclusion of isopropanol led to a deterioration in fuel consumption and increased levels of NO_x pollutants. However, an improvement in smoke emissions was observed.

Indeed, it is worth noting that there have been relatively few studies conducted thus far focusing specifically on the environmental and economic influences of diesel-alternative fuel blends. While there has been significant research on the performance and emissions aspects of alternative fuels, the broader assessment of their overall environmental effects and the economic implication of their implementation is an area that warrants further investigation. Expanding the scope of research to encompass these dimensions would provide valuable insights into the broader sustainability and viability of alternative fuels as a whole. The research conducted by Caliskan [18] delved into comprehensive environmental and cost analyses of certain biodiesel fuels, namely soybean oil methyl ester (SO), high oleic soybean methyl ester (OS), and conventional diesel (CD). The findings indicated that OS biodiesel showcased the most favorable environmental effects compared to the other tested fuels. On the other hand, SO biodiesel exhibited poorer environmental performance in comparison. A similar trend was observed in the enviro-economic analysis, with OS biodiesel demonstrating the lowest carbon dioxide (CO_2) emission cost among the tested fuels, while SO biodiesel exhibited the highest cost in this regard. Selçuk [19] has focused on the environmental and economic evaluation of methanol-gasoline and methanol-hydrogen-gasoline blends in an SI engine. The results indicate that the addition of methanol slightly increases the annual CO2 environmental impact (by 0.11%), while the addition of hydrogen reduces the CO2 environmental impact (by 1.89%). The author suggests that further research is needed for the environmental and cost assessment of alternative fuels. Gurbuz et al. [20] conducted an experimental study to investigate the effects of liquefied petroleum gas (LPG) on environmental and cost aspects in a spark ignition (SI) engine. The study reached the conclusion that there is a direct relationship between engine power and the environmental cost of pollution, as well as the annual generation of CO_2 emissions by the engine. In other words, as engine power increases, so does the associated cost and CO_2 emissions generated annually by the engine. Yildiz et al. [21] conducted a study that focused on the cost analysis of a blend of waste cooking oil biodiesel and standard diesel fuel. The findings revealed that conventional diesel demonstrated superior environmental characteristics when compared to biodiesel. As a result, diesel fuel was suggested as the preferred option due to its slightly better environmental pollution performance, specifically in terms of the cost associated with CO_2 emissions.

Existing literature predominantly emphasizes combustion, engine performance, and emissions in the context of alternative fuels, with limited attention given to the environmental influence and cost dimensions. Consequently, there is a dearth of published research papers that specifically explore the environmental influence and cost analysis aspects of alternative fuels. Therefore, this study aims to focus on the environmental impact and cost analysis of alternative fuels. Given the frequent use of ethanol and isopropanol alcohols as main fuel additives in the literature, it is of utmost importance to determine their environmental impact and environmental cost, in addition to their effect on emissions. The study was conducted under 3 and 6 Nm engine torque conditions with variable engine speeds. Ethanol and isopropanol were added to diesel fuel individually at a volumetric fraction of 7%.

II. MATERIALS AND METHOD

The experimental examinations were conducted using a single-cylinder, air-cooled, direct injection CI engine (AD320 brand) manufactured by Anadolu Motor. The AD320 diesel engine's mechanical injector features a total of four nozzles. It has two valve ports, one for intake and one for exhaust, with overhead camshaft configuration. The AD320 diesel engine has a total displacement of 315 cc and a compression ratio of 17.5. The AD320 small diesel engine was coupled to an ABB brand dynamometer. Subsequently, using a LABVIEW-based programmable software, the engine torque and speed were adjusted according to the test matrix. The ABB brand dynamometer has maximum measurement values of 50 kW for engine power, 157 Nm for torque, and 6000 rpm for engine speed [22, 23].

The primary fuel (diesel) was obtained from a local fuel company, while ethanol and isopropanol were sourced from a local chemical company. The test fuel blends were prepared by volumetrically adjusting the proportions using graduated measuring cups. The physicochemical properties of these fuel blends are provided in Table 1.

Table 1. Physicochemical properties of test fuels [11, 22].

Properties	**Diesel**	**Ethanol**	**Isopropanol**
Mol. formula	C_xH_y	C_2H_5OH	C_3H_7OH
Density (g/cm^3)	0.83-0.84	0.789-0.8	0.8-0.805
Mol. wt. (Kg/kmol)	185-212		60.1
C wt. (%)	86.1	52.14	60
H wt. (%)	13.9	13.02	13.3
O wt. (%)	-	34.73	26.6
Cetane number	45-52	8-10	10-12
Viscosity at 40ºC (cm/s^2)	0. 27	0.113	0. 17

Table 2 illustrates the volumetric fractions of the test fuels utilized in the experiments. The diesel test fuel was prepared by blending 7% ethanol and 7% isopropanol by volume, respectively. The experiments were initially conducted using standard diesel fuel (Case 1). Subsequently, 7% ethanol was volumetrically added to the diesel fuel, and the experiments were carried out as Case 2. Finally, 7% isopropanol was volumetrically added to the standard diesel fuel, and the experiments were performed. Table 2 also presents the experimental steps (Case 1, Case 2, and Case 3) undertaken in the study.

Table 2. The volumetric composition of the respective fuel blends used in the experimental study.

Test	Diesel v/v%	Ethanol v/v%	Isopropanol v/v%	Abbv.
Case 1	100	-	-	Diesel
Case 2	93	7	-	E7
Case 3	93	-	7	IP7

Engine-out emissions of HC, CO, CO_2, and NO were measured using the BOSCH BEA60 emission analyzer, which has a volume sensitivity of 0.01% [24]. The emissions outputs of Case 1 (standard diesel fuel), Case 2 (93% diesel + 7% ethanol), and Case 3 (93% diesel + 7% isopropanol) were comparatively analyzed. The BOSCH BEA60 model emission device allowed for accurate measurement and comparison of emissions between the different fuel blends.

The present investigation entails the evaluation of environmental and costs associated with combustion-derived emissions in diesel fuel, as well as their respective blends with ethanol and isopropanol. In this particular scenario, the parameter of environmental influence (X_i) and cost factor (C_i) are employed, which is computed using the following equation (1) and (2), respectively [25]:

$$X_i = \dot{m}_e . x_{ei} \quad (1)$$

$$C_i = \dot{m}_e . c_{ei} \quad (2)$$

wherein, '$\dot{m}_e$' denotes the mass flow rate of the harmful gas measured in kilograms per hour (kg/h). Additionally, 'x_{ei}' represents the specific environmental influence points as outlined in Table 3, with its unit expressed as mPts/kg. Also, where, c_{ei} symbolizes the environmental cost and its unit is Euro/kg.

As in the previous study [25], in the cost analysis, the dollar/euro ratio was chosen to correspond to 0.953 euro units. Moreover, for the purpose of this analysis, the HC harmful gas was assumed to be equivalent to CH_4 (methane).

Table 3. Environmental influence and eco-cost values associated with harmful emissions resulting from combustion [25, 26].

Harmful gas	Environmental influence, x_{ei}	Environmental Cost, c_{ei}
HC	~0.115	~3.87
CO	~0.0084	~0.26
CO_2	~0.0055	~0.13
NO	~2.75	~6.95

III. RESULTS

A. *Emission Characteristics*

Fig. 1 illustrates the variations in HC emission values for test fuels at 3 and 6 Nm engine torque and various engine speeds. At idle speeds and high engine speeds, HC emissions increase, while at the speed range where maximum torque occurs (1850 rpm [22]), HC emissions decrease. Increasing the engine load leads to a more stable combustion phase, resulting in a slight reduction in HC emissions. The unstable combustion phase at low speeds contributes to an increase in HC emissions. At high engine speeds, the shortened intake duration in the cylinder relatively reduces the air/fuel ratio, resulting in a rich mixture. As a result, HC emissions increase. The lowest HC emission formation was achieved by using a diesel blend with ethanol. The high oxygen concentration in ethanol has contributed to the reduction of HC emissions.

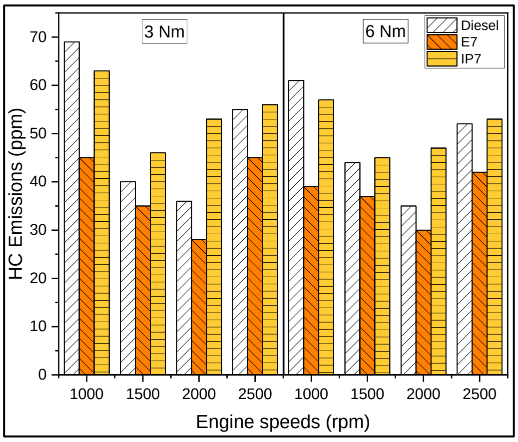

Fig. 1 Variation of HC emissions during variable engine speeds and torques.

Fig. 2 illustrates the variations in CO emission values for test fuels at 3 and 6 Nm engine torque and various engine speeds. When there is insufficient oxygen density within the cylinder, carbon (C) cannot convert into CO_2, resulting in the emission of CO [25]. As shown in Fig. 2, an increase in engine speed has contributed to the reduction of CO emissions. This can be attributed to the occurrence of a more stable combustion phase and an increase in the amount of air intake into the cylinder. On the other hand, the addition of ethanol and isopropanol to diesel has contributed to the decrease in CO emissions at low and high engine speeds. Ethanol and isopropanol additives increase the oxygen (O_2) concentration in the mixture, leading to a decrease in CO emissions.

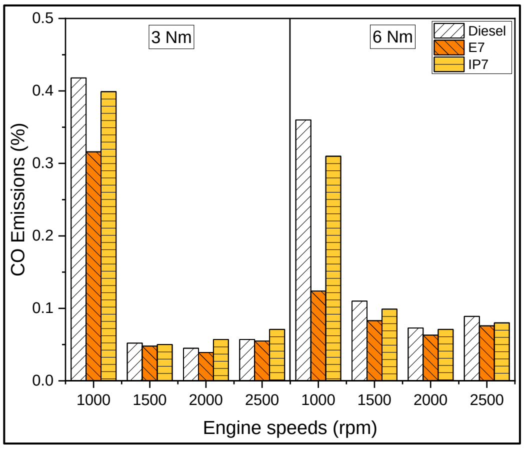

Fig. 2 Variation of CO emissions during variable engine speeds and torques.

Fig. 3 illustrates the variations in CO_2 emission values for test fuels at 3 and 6 Nm engine torque and various engine speeds.

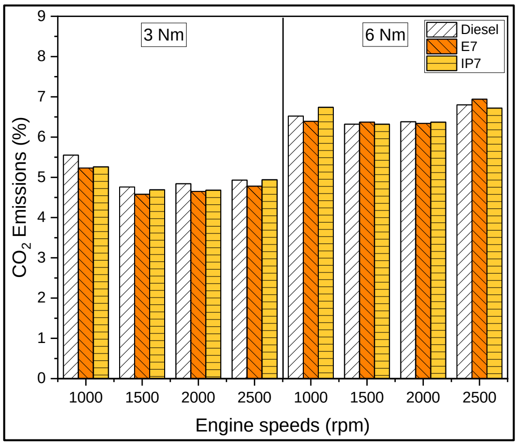

Fig. 3 Variation of CO_2 emissions during variable engine speeds and torques.

CO_2 emissions have increased with an increase in engine load. This can be attributed to the rise in fuel injection quantity into the cylinder and the increase in the amount of O_2 utilized during combustion. While alcohol additives to diesel have shown no significant impact on CO_2 emissions under low loads, they have contributed to a reduction in CO_2 emissions under high load conditions. The alcohol additives facilitate more complete and efficient combustion during the combustion process, leading to a higher conversion of fuel into energy. Consequently, this results in a decrease in CO_2 emissions and a lower C footprint.

Fig. 4 illustrates the variations in NO emission values for test fuels at 3 and 6 Nm engine torque and various engine speeds. For both engine loads, an increase in engine speed has contributed to a reduction in NO emissions. The lowest NO emission values were achieved when using conventional diesel across all engine loads and speeds. However, the introduction of alcohol into diesel fuel resulted in a slight increase in NO emissions. The high O_2 content of ethanol and isopropanol alcohols can be identified as the most significant factor contributing to the increase in NO emissions. On the other hand, an increase in engine load and the resulting rise in combustion temperatures have also contributed to an increase in NO emissions. The highest NO emissions were observed with diesel-ethanol fuel mixture at 6 Nm engine load and 1500 rpm engine speed. The lowest NO emissions were achieved with conventional diesel at 3 Nm engine load and 2500 rpm engine speed.

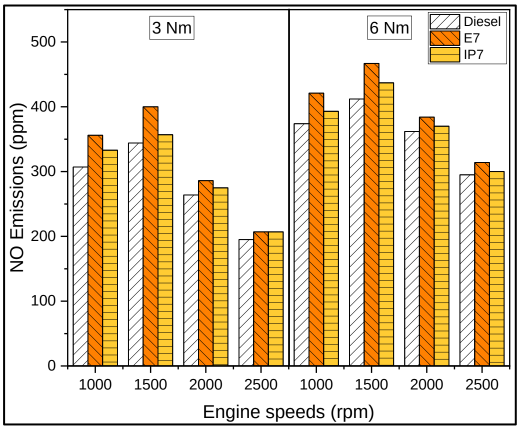

Fig. 4 Variation of NO emissions during variable engine speeds and torques.

B. Environmental Influence and Cost Analysis

Evaluating the performance and assessing viability of alcohol in diesel engines necessitates a comprehensive examination of the environmental implications and cost factors associated with alcohol-diesel blends. In the conducted study, the mass flow consumption (in g/h) of emitted harmful gases during the one-hour operation of a small diesel engine was considered. Fig. 5 illustrates the variations in environmental influence values of emitted harmful emissions for test fuels at 3 Nm engine torque and various engine speeds. The highest environmental impact caused by harmful gases was observed with a fuel mixture of 93% Diesel + 7% Ethanol at an engine speed of 1000 rpm, while the lowest environmental impact was exhibited by fuel blends of 93% Diesel + 7% Ethanol and 93% Diesel + 7% Isopropanol at high engine speeds (2500 rpm). At 3 Nm engine torque and 1000 rpm engine speed, the addition of ethanol to diesel fuel has increased the environmental influence by 13.4%. Under the same engine torque conditions and at 2500 rpm engine speed, the additions of ethanol and isopropanol have reduced the environmental influence by 44.8% and 44.6%, respectively, compared to diesel fuel. The addition of ethanol and isopropanol to diesel fuel at low and medium engine speeds in a 3 Nm motor load significantly increased the environmental impact due to the elevated NO emissions. However, at high engine speeds, the reduction of NO emissions through alcohol additives resulted in a decrease in environmental impact.

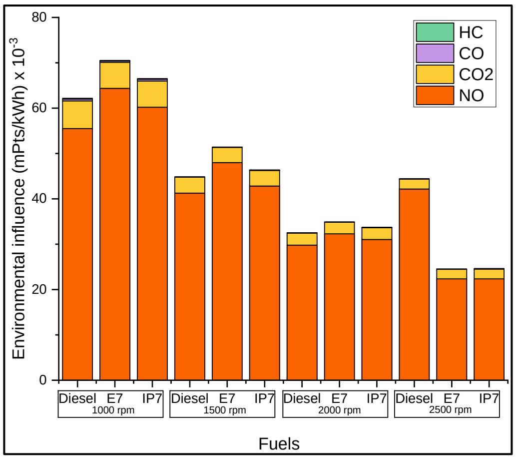

Fig. 5 The environmental influence of emissions during variable motor speeds at 3 Nm motor torque.

Fig. 6 illustrates the variations in environmental influence values of emitted harmful emissions for test fuels at 6 Nm engine torque and various engine speeds. With an increase in engine load, environmental influence values decreased at all engine speeds. The increase in engine power allows for higher fuel injection into the cylinder, resulting in the release of more energy. This leads to the attainment of higher combustion temperatures, promoting a more stable combustion phase [24]. Consequently, more stable combustion leads to lower emissions. Lower emissions, in turn, contribute to a reduced environmental influence. The highest environmental influence at 6 Nm engine torque was achieved at an engine speed of 1000 rpm with the diesel-ethanol blend, while the lowest environmental impact was obtained at 2500 rpm with the diesel-alcohol blends. At 6 Nm engine torque and 1000 rpm engine speed, the addition of ethanol to diesel fuel has increased the environmental influence by 10.7%. Under the same engine torque conditions and at 2500 rpm engine speed, the additions of ethanol and isopropanol have reduced the environmental influence by 18% and 21.6%, respectively, compared to diesel fuel.

As seen in Fig. 5 and Fig. 6, the most significant emission values that affect the environmental influence parameter are NO and CO_2. The mitigation of these two emissions in diesel engines contributes to a notable reduction in environmental influence.

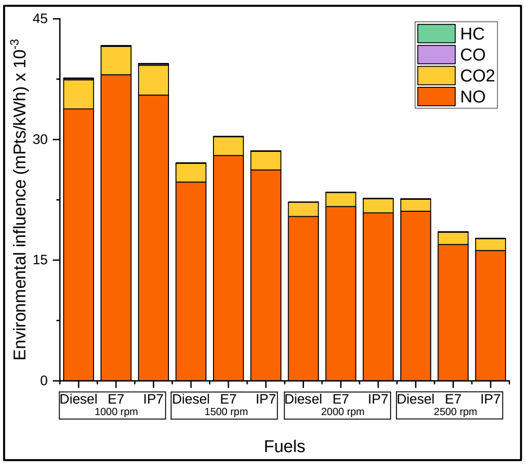

Fig. 6 The environmental influence of emissions during variable motor speeds at 6 Nm motor torque.

Fig. 7 illustrates the variations in cost values of emitted harmful emissions for test fuels at 3 Nm engine torque and various engine speeds. The highest cost caused by harmful gases was observed with diesel fuel at an engine speed of 1000 rpm, while the lowest environmental cost was exhibited by fuel blends of 93% Diesel + 7% Ethanol and 93% Diesel + 7% Isopropanol at high engine speeds (2500 rpm). The increase in engine speed had a significant impact on the environmental cost and provided more than a 50% reduction. In addition, the augmentation of ethanol and isopropanol to diesel has resulted in a marginal reduction in environmental costs.

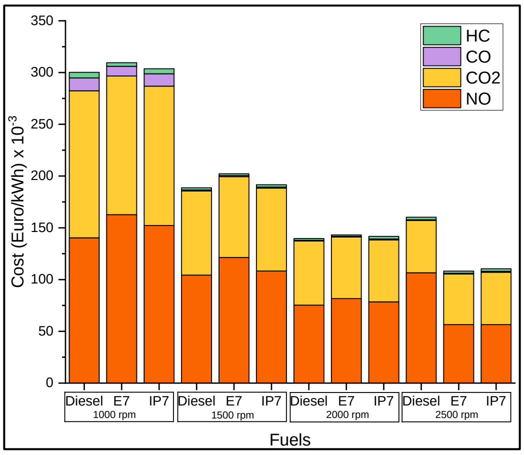

Fig. 7 The environmental cost of emissions during variable motor speeds at 3 Nm motor torque.

Fig. 8 illustrates the variations in cost values of emitted harmful emissions for test fuels at 6 Nm engine torque and various engine speeds.

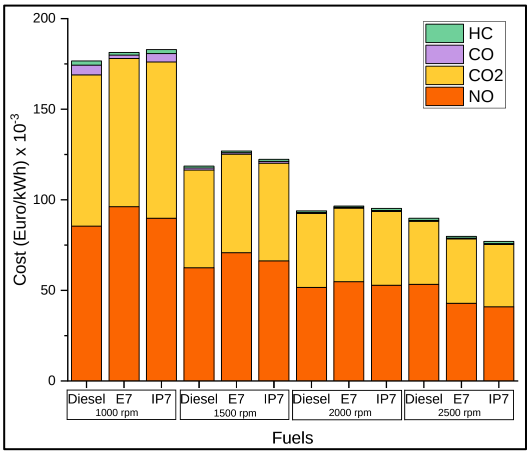

Fig. 8 The environmental cost of emissions during variable motor speeds at 6 Nm motor torque.

With an increase in engine load, cost values decreased at all engine speeds. Similar to the 3 Nm engine torque condition, at an engine torque value of 6 Nm, CO_2 emissions appear to have a more dominant impact on environmental costs compared to NO emissions. Also, the high levels of CO emissions at 1000 rpm engine speed have also contributed to the high environmental costs. At 6 Nm engine torque, the highest cost caused by harmful gases was observed with 93% Diesel + 7% Isopropanol blend at an engine speed of 1000 rpm, while the lowest environmental cost was exhibited by fuel blends of 93% Diesel + 7% Ethanol and 93% Diesel + 7% Isopropanol at high engine speeds (2500 rpm). At 1000 rpm engine speed, the contribution of CO_2 to environmental costs for the blend of 93% Diesel + 7% Isopropanol is approximately 47%, while at 2500 rpm engine speed, this percentage is around 45%.

IV. CONCLUSION

The conclusions of emission measurements and environmental-economic analysis of diesel and alcohol-diesel mixtures carried out in a single-cylinder diesel engine are summarized below.

- Under low load conditions, due to the presence of a more unstable combustion phase, HC and CO emissions are high. However, with an increase in load, both NO and CO_2 emissions have increased, while HC and CO emissions have relatively decreased.
- Higher HC and CO emissions were obtained at lower engine speeds. As the engine approached its maximum torque speed, the amount of air entering the cylinder increased, leading to an increase in NO emissions.
- The addition of ethanol and isopropanol to diesel fuel has reduced HC and CO emissions. However, due to the high O_2 content in alcohol fuels, it has resulted in an increase in NO emissions.
- The addition of alcohol to diesel has resulted in an increase in NO emissions due to the increased O_2 concentration in the mixture, leading to a significant increase in environmental impact. NO emissions have contributed over 80% to the overall increase in environmental influence.
- While an increase in engine speed may reduce environmental costs, the addition of alcohol (such as ethanol and isopropanol) to diesel has contributed to an increase in environmental costs.

In future studies, the reduction of NO emissions and the mitigation of environmental and economic impacts can be achieved by implementing alternative gaseous fuels such as methane, biogas, and hydrogen in a dual-fuel concept, rather than alcohol additives to diesel.

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