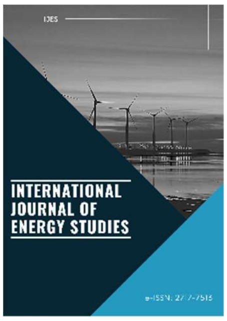
INTERNATIONAL JOURNAL OF ENERGY STUDIES

e-ISSN: 2717-7513 (ONLINE); homepage: https://dergipark.org.tr/en/pub/ijes



Research Article

Int J Energy Studies 2023; 8(4): 831-847

DOI: 10.58559/ijes.1366789

Received	:	26 Sep 2023
Revised	:	28 Oct 2023
Accepted	:	01 Nov 2023

The assessment of performance and emissions characteristics of a CI engine running on waste tyre pyrolysis oil as an alternative fuel and its blends with diesel fuel

Talha Ertürk[a], Ahmet Arslan[a], Erdal Tunçer[b, c], Battal Doğan[a], Murat Kadir Yeşilyurt[d*]

[a]*Department of Energy Systems Engineering, Faculty of Technology, Gazi University, Ankara, Türkiye, ORCID: 0009-0007-5467-9249, ORCID: 0009-0003-7075-3446, 0000-0002-5904-0942*

[b]*Erin Engine Corporation Inc., Department of Research and Development, İstanbul, Türkiye, ORCID: 0000-0002-5212-0966*

[c]*Department of Mechanical Engineering, Faculty of Engineering and Natural Sciences, Istanbul Health and Technology University, İstanbul, Türkiye, ORCID: 0000-0002-5212-0966*

[d]*Department of Mechanical Engineering, Faculty of Engineering-Architecture, Yozgat Bozok University, Yozgat, Türkiye, ORCID:0000-0003-0870-7564*

*(*Corresponding Author: kadir.yesilyurt@bozok.edu.tr)*

Highlights

- Evaluating waste tyres as a fuel after converting them to valuable products
- Testing WTPO/DF blends in a diesel engine
- Higher fuel consumption for WTPO because of lesser energy content
- Need to be enhanced the specifications of WTPO
- Providing more detailed information through thermodynamic, economic, and environmental analyses

You can cite this article as: Ertürk T, Arslan A, Tunçer E, Doğan B, Yeşilyurt MK. The assessment of performance and emissions characteristics of a CI engine running on waste tyre pyrolysis oil as an alternative fuel and its blends with diesel fuel. Int J Energy Studies 2023; 8(4): 831-847.

ABSTRACT

The target of the present research is to examine the performance and emissions of waste tyre pyrolysis oil (WTPO) added into diesel fuel (DF) at different percentages in a compression-ignition (CI) engine. In the engine, tests were undertaken at four ranging loads (25%, 50%, 75%, and 100%) at 1500 rpm. The lower viscosity and energy content of WTPO compared to DF affected performance and emissions. Adding WTPO to DF increased fuel consumption, CO2, HC, and CO emissions, while reducing exhaust gas temperature (EGT). At the same load, HC emission increased by 13.3% as the fraction of WTPO in the blend ascended. While the EGT value of DF was 261oC at 25% load, this temperature dropped to 251oC for P40 fuel. When the load was 25%, the amount of CO2 emission ascended between DF and P40 fuel was 38.67%, while this increment reached 59.5% at the highest load. In the study, monthly CO2 emissions of fuel blends were calculated. In line with these calculations, it has been deemed environmentally appropriate to use end-of-life (EOL) tyres as fuel instead of scrapping them.

Keywords: Diesel, Pyrolysis oil, Emissions, Performance, Waste tyre

1. INTRODUCTION

The need for energy, which is increasing and continues to ascend in the world, is a remarkable requirement. This fact pushes mankind to search for new, clean, and alternative options to meet the demand. The widespread consumption of currently used petroleum-based fuels in the field of transportation and the limited resources constitute a disadvantage for future needs. On the other hand, automotive manufacturing is increasing every year. This situation also affects tire production all over the world. In this sense, the quantity of waste tyres is rising in the transportation sector day by day. Vehicle tyres complete their life after a certain number of kilometers. Since vehicle use continues, tyres are replaced. The disposal of EOL tyres constitutes a very significant environmental issues. It is estimated that the value of EOL tyres in worldvide reaches annually of around 1.5 billion. In other words, the weight of these waste tyres reaches approximately 17 million tons [1].

In Türkiye, the amount of EOL tyres is 180,000-300,000 tons every year [2]. The fact that EOL tyres disappear long period in nature poses major problems. The damage of chemical wastes to the environment and the emissions resulting from the burning of tyres are among the major problems. Research on alternative and environmentally-friendly fuels is considerable in terms of evaluating waste tyres in different ways, reducing the harmful impacts of EOL tyres on the human health and environment, and providing profit. In the literature, there are a number of studies on the practice of WTPO derived from scrap materials or waste vehicle tyres in CI engines by inclusion in fuels as a high-value by-product.

Waste oils can be used effectively and economically as fuel by performing some chemical processes [2]. One of the most promising options for this situation is the usage of pyrolysis oil as an alternative fuel in CI engines. In an engine where Euro pyrolysis tyre oil was used as fuel, it was monitored that HC, CO, and soot emissions mitigated while NO_X emissions ascended [3]. Hürdoğan et al. [4] conducted research on the performance and emission patterns of a four-cylinder CI engine operating with WTPO-DF blends. In the study, the properties of the blends, engine performance and emission behaviors were mainly considered and benchmarked against the conventional DF. According to the experimental outcomes, the researchers determined that the fuel blends showed similar performance with DF. It was emphasized that these blends for diesel engines are valid not only for performance output and properties but also for environmental subjects. The influence of pyrolysis oil from waste tyres on the performance and emission parameters in diesel engines can be determined with computer-aided software. Within the scope of the research conducted by Uçar [5], it was indicated that the oil produced from waste tyres added to DF reduced in-cylinder pressures and slowed down the rate of heat release rate. Uslu [6] investigated the influences of injection pressure and load changes in a CI engine using WTPO-DF blends prepared by mixing with DF at different fractions under laboratory conditions and analyzed using response surface methodology (RSM). Based on the results of the study, the optimum operating parameters were noted as WTPO ratio of 30.51%, load of 62.12%, and injection pressure of 225 bar.

The engine octane number for pyrolysis oil is lower than that of gasoline and much higher than that of DF [7]. Waste vehicle tyre chips can be pyrolyzed to reach liquid oil forms. In addition, waste tyre oil has a low flash point, low cetane number, and high density. It can reduce pollutant emissions when blended with traditional DF [8]. Energy, exergy, sustainability and thermoeconomic analyses of WTPO and DF blends are available in the literature [9, 10]. In these studies, analyses were performed at different loads and with different fuel blend concentrations.

When pyrolysis oil is used in a CI engine, fuel properties need to be improved for more efficient combustion. In fuel blends using pyrolysis oil, purification processes enhance fuel characteristics. The oxygen and carbon content of tyre pyrolysis oil is close to DF, but the hydrogen content is higher than DF. There is no noticeable change in CO and NO_X emissions in fuel blends using pyrolysis oil compared to mineral DF. Increasing the pyrolysis oil proportion in pyrolysis oil-DF blends significantly descended HC emissions [11]. Martinez et al. [12] considered pyrolysis as an appealing thermochemical process to deal with waste tyre disposal. A comprehensive review of the renewable energy recovery of the the substantially natural rubber contained in tyres and the pathway to energy from waste was conducted. Special attention was paid to the liquid fraction and its importance was emphasized.

Waste tyre oil is mainly composed of alkanes and aromatic hydrocarbons, and contains nitrides, sulfides, and polyaromatic hydrocarbons [13]. İlkılıç and Aydın [14] marked that alternative fuel production can be realized by pyrolysis of waste vehicle tyres under nitrogen conditions using $Ca(OH)_2$ as a catalyst. Martinez et al. [15] studied the blending of a tyre pyrolysis liquid fuel produced in a continuous auger reactor at an initial scale. The researchers investigated the pyrolysis concentration for the production of liquid fuels that can be used very limitedly in automotive engines. Lewandowski et al. [16] examined the current utilization, structures, and operating principles of different pyrolytic reactors. Kumaravel et al. [17] discussed the pyrolysis mechanism, pyrolysis reactors, product yields, approximate characteristic analysis of tyres, elemental analysis and pyrolysis process in their review paper. The researchers highlighted that NO_X, CO, HC, and smoke emissions were higher at higher loads. Wang et al. [18] pyrolyzed waste tyres at various reaction temperatures in a laboratory-scale fixed bed reactor. The researchers compared the yields of liquid, solid, and gaseous products obtained from different pyrolysis temperatures with experimental data, as well as property and elemental analysis for the petroleum product. Besides that, the fuel consumption, engine performance, in-cylinder pressure, engine power, and SO_2 emissions were analyzed. As a result, it was determined that increasing the addition of waste tyre oil percentage to DF had a negative impact on the engine performance. However, as the pyrolysis temperature of the waste tyre oil to be used increased, it contributed positively to the usability of the product obtained. Ruwona et al. [19] reported in their work that further processing of pyrolysis oil and char from reacting waste tyres in a laboratory-scale fixed bed reactor and having a viable market for the resultant outputs would drastically upgrade the economics of the process. Yaqoob et al. [20] used graphite nanoparticles, Fe_2O_3 nanoparticles, and waste tyre oil in gasoline blends at different concentrations and compared the prepared blends with pure gasoline in terms of energy, exergy, economical, and sustainability perspectives. The researchers used blends containing 40, 80, and 120 mg/L graphite nanoparticles and Fe_2O_3 nanoparticles as well as 5% and 10% waste tyre oil by volume and conducted the tests in a single-cylinder, air-cooled, four-stroke engine at various loads between 2 Nm and 10 Nm. The researchers obtained maximum energy and exergy efficiency values of 21.94% and 23.05% for the P120FO blend at 8 Nm load, respectively. It was determined the highest sustainability index as 1.3 for the P120FO. In addition, it was obtained the minimum exhaust energy ratio as 0.03241 kW for P120FO. To conclude, the best results in view of energetic and exergy efficiencies, and sustainability index were achieved with P120FO in comparison to gasoline.

Considering the studies reported in the relevant literature, the effects of the addition of pyrolysis oil from EOL tyres to DF at different ratios have been investigated in various aspects. In this study, the performance and emission parameters of commercial DF and its blends with WTPO at varying loads were determined through tests and evaluated in a view to environmental pollution. The environmental pollution caused by CO_2 in the case of using EOL tyres as fuel was compared with the impact of leaving them in the environment as scrap.

2. MATERIALS AND METHOD

The materials, measuring devices, equipments, and methods used in this study are presented systematically below.

2.1. Test Fuels

In this study, the effect of using different ratios of DF and WTPO blends on the engine performance and exhaust emissions in a CI engine was experimentally investigated. Some important properties of DF and WTPO used as base fuels are given in Table 1. Fuel tests were carried out in the laboratories of Yozgat Bozok University Science and Technology Application and Research Center.

Table 1. Properties of DF and WTPO

Property	Unit	DF	WTPO	Method
Lower heating value	MJ/kg	42.42	32.78	ASTM D 240
Density (at 15ºC)	kg/m^3	832	824.13	ASTM D 5002
Kinematic viscosity (at 40ºC)	mm^2/s	3.02	2.53195	TS 1451 ISO 3104
Flash point	ºC	60	38	TS EN ISO 2719
Sulphated ash content	%	0.018	0.031	TS EN ISO 6245

The fuel blends used in the study were obtained by adding pyrolysis oil to DF at different concentrations. The volumetric ratios of the fuel blends and their significant properties depending on the fuel type are presented in Table 2.

Table 2. Volumetric mixing ratios of experimental fuels and some properties of these mixtures

Test fuels	DF (%)	WTPO (%)	Lower heating value (MJ/kg)	Kinematic viscosity (mm^2/s)	Density (kg/m^3)
P10	90	10	41.46	2.97	831.21
P20	80	20	40.50	2.94	830.42
P30	70	30	39.52	2.87	829.63
P40	60	40	38.56	2.81	828.85

2.2. Engine Tests

DF and WTPO-DF blends with different ratios were used in this study. In order to get the performance and emission data of the aforementioned test fuels, a single-cylinder CI engine whose technical specifications was operated and it's technical specifications were tabulated in Table 3.

Table 3. Specifications of the engine recognised in the experiments

Brand – Model	Sincro – SK160 CB
Fuel type	DF
Engine type	4-stroke, Direct-injection
Cylinder number	1
Cylinder volume	1.16 m^3
Bore	108 mm
Stroke	127 mm
Valve number	4
Compression ratio	14.6:1
Maximum torque	60 Nm (at 1500 rpm)
Maximum power	10 kW (at 1500 rpm)
Cooling type	Water-cooled
Intake system	Naturally-aspirated

In this work, DF was purchased from a petrol stations and WTPO was obtained from a commercial company. WTPO was mixed with DF at different ratios by volume. The fuel mixtures were kept for a certain period of time and no phase separation was monitored. The prepared test fuels and the DF used as the reference were subjected to various loads at constant speed in the engine. The engine test setup is schematically given in Figure 1. Before the diesel engine was operated with the test fuels, it was run at idle speed for a while to acquire more accurate results in a steady-state condition. Then the fuel blends (P10, P20, P30, and P40) were put into the fuel tank and tested in order for obtaining experimental data. The outcomes of the tests performed at different loads for each blend were determined and recorded with the help of measuring devices.

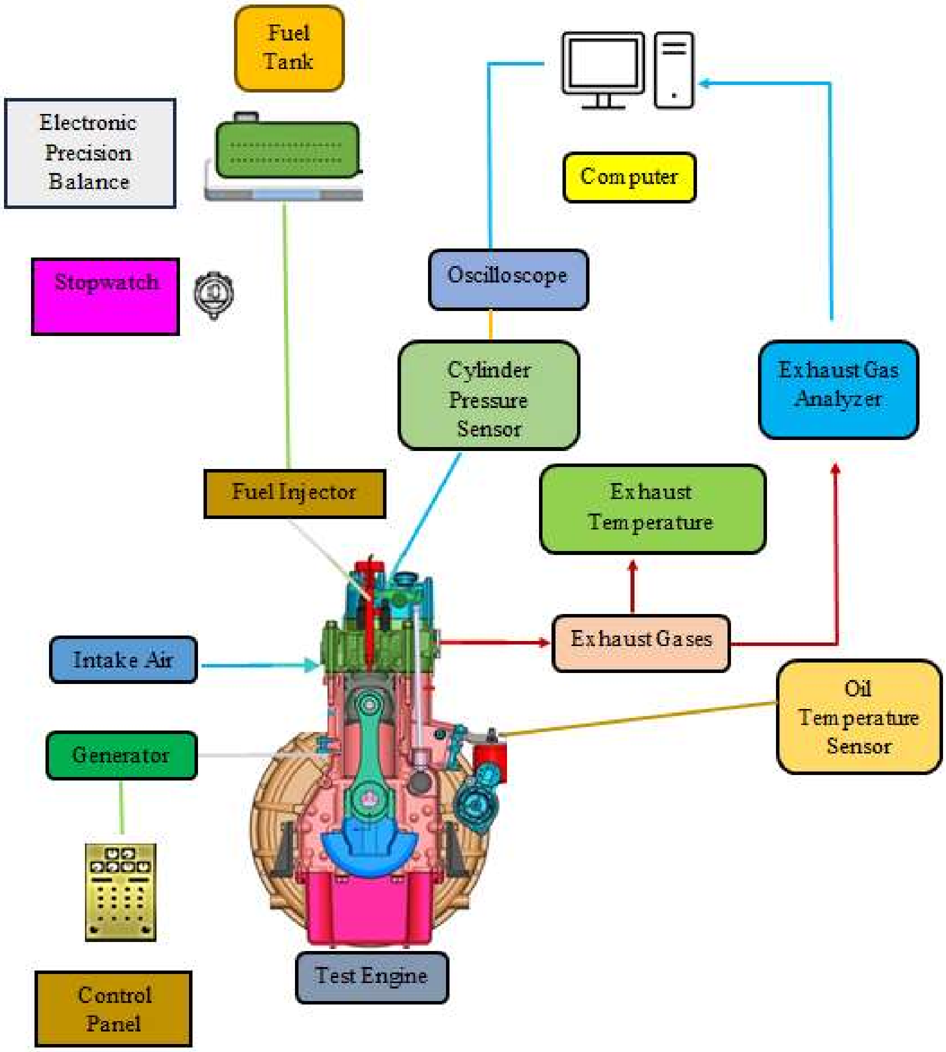


Figure 1. Schematic view of the test setup

3. RESULTS AND DISCUSSION

In the present investigation, WTPO-DF blends were subjected to conditions of ranging loads, and thence performance and emission values were recorded. In a single-cylinder CI engine, experiments were first conducted with DF. Fuel blends were used in subsequent tests.

3.1. Fuel Consumption

Figure 2 shows the fuel consumption values of the test fuels at four different loads. For all fuel blends, fuel consumption decreased with increasing load. For P40 fuel, fuel consumption at 25%, 50%, 75%, and 100% loads were noted to be 0.431 kg/h, 0.395 kg/h, 0.372 kg/h, and 0.367 kg/h, respectively. Fuel consumption ascended with increasing pyrolysis oil ratio. For instance, the fuel consumption values were found to be 0.322 kg/h for D100, 0.334 kg/h for P10, 0.342 kg/h for P20, 0.351 kg/h for P30, and 0.367 kg/h for P40 at 100% load. As a result, it was observed that the fuel consumption varied inversely with the increase in load but increased in direct proportion with the amount of pyrolysis oil in the blend. This may be because of the increase in temperature values inside the cylinder [3]. At an increase of 10% pyrolysis oil by volume added to DF, an increase of approximately 2.48% was observed at each load. İsmailoğlu [21] emphasized that brake specific fuel consumption values of 10% pyrolysis oil-90% DF were acquired to be 8% higher at the speed of 1500 rpm, approximately 7.8% higher at the speed of 1800 rpm, and approximately 8.1% higher at the speed of 2100 rpm in comparison with DF.

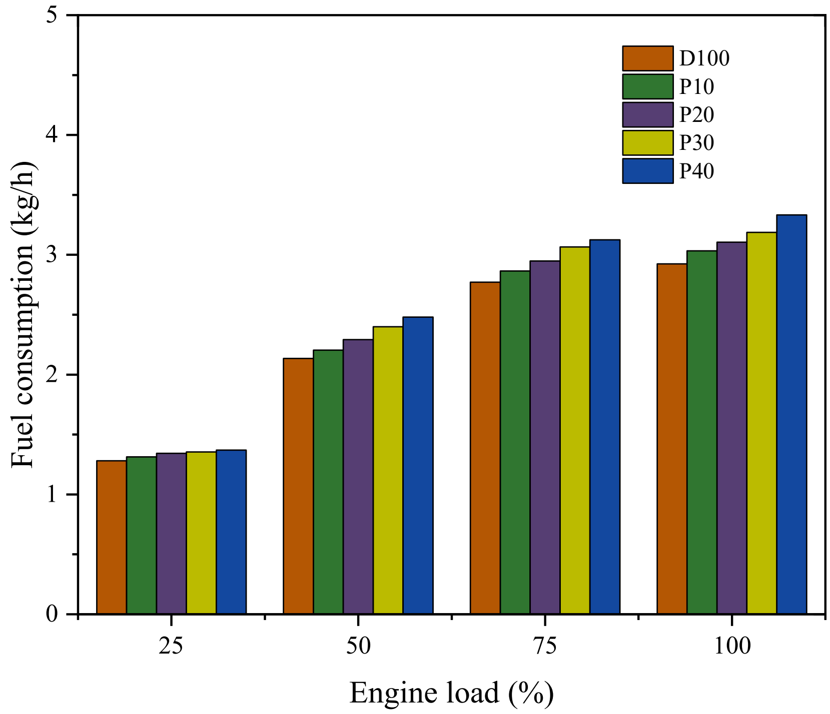


Figure 2. Load-dependent change in fuel consumption emissions for test fuels

3.2. Exhaust Gas Temperature

In internal combustion engines, heat is released due to combustion in the cylinder. A certain part of this heat is converted into mechanical energy (useful work). The part that cannot be converted into useful work is discharged from the engine to the atmosphere through exhaust gases, lubrication, and cooling. As seen in Figure 3, as WTPO was added to DF, EGT values were reduced slightly. While the EGT value of D100 fuel was measured to be 261°C at a load of 25%, this value declined to 251°C for P40 fuel. When the literature is examined comprehensively, pyrolysis oil, which has high volatility, tends to evaporate by absorbing the heat in the cylinder, reducing the ambient temperature [22]. Another reason regarding the lower temperature is the energy content of the tested fuel samples. Table 1 was taken into consideration, WTPO addition to the mineral DF led to a decline in the energy content of the blend. Thus, less heat occurred during the combustion process inside the cylinder. To conclude, EGT was mitigated when the engine was run on fuel blends in the present research. Additionally, due to the lower temperature of the WTPO ratio in fuel blends, less expansion reduces exhaust temperatures [23]. While the EGT of P30 fuel was measured to be 383ºC at the load of 50%, the value of the same fuel blend at 75% load was measured as 516ºC. In conclusion, EGT ascended with increasing load.

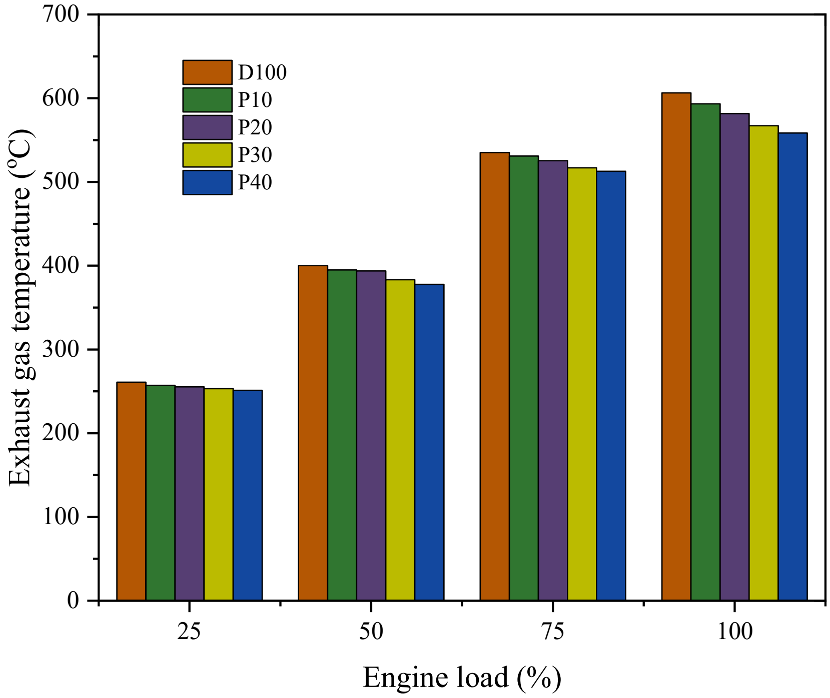


Figure 3. Load-dependent change in EGT emissions for test fuels

3.3. Hydrocarbon (HC) Emission

HC emission in internal combustion engines indicates that the fuel taken into the cylinder goes out without participating in the combustion process. Insufficient oxygen in the engine's internal volume plays a role in increasing HC emissions. When Figure 4 was analyzed, it was determined that HC emission decreased by 17.6% for P20 fuel from 25% to 50% load. Accordingly, a reduction in HC emission was observed in other fuel blends because of increasing loads. The presence of pyrolysis oil in the fuel blends descended the viscosity of the fuel and ascended the HC emissions [24]. At the highest load, the HC emissions increased from 4 ppm to 9 ppm as the amount of pyrolysis oil increased in the blend.

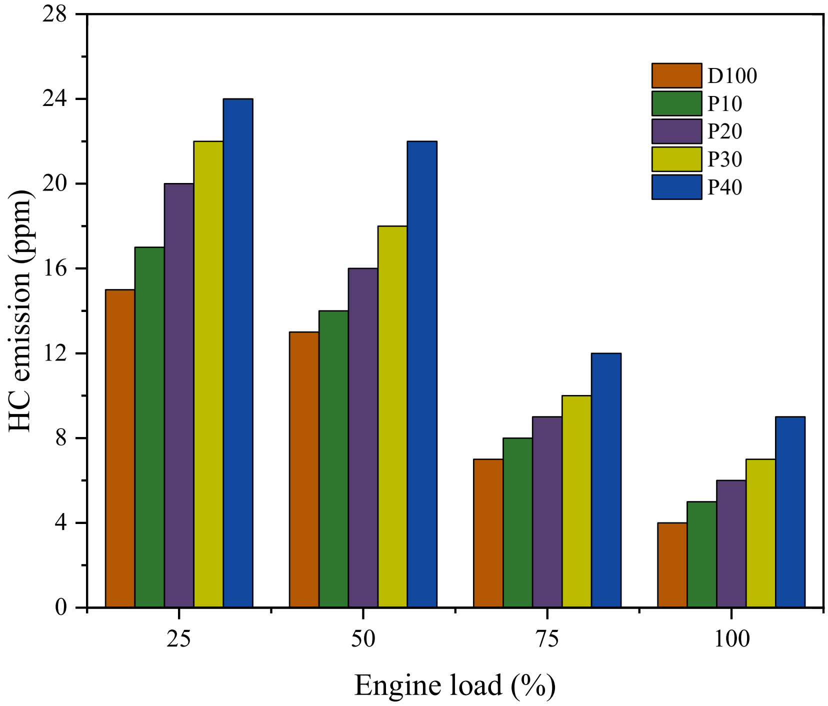


Figure 4. Load-dependent change in HC emissions for test fuels

3.4. Carbon Monoxide (CO) Emission

In diesel engines, incomplete combustion occurs due to the insufficient duration required for the combustion reaction of fuels in the cylinder. On this basis, CO emissions appear through incomplete combustion. Incomplete combustion occurs depending on the increased rate of WTPO in the fuel blend. As can be seen in Figure 5, the CO emission value at 25% load was found to be 0.031% for D100 fuel while it was 0.088% for P40 fuel. WTPO, which has high volatility, affects cooling process and causes CO emissions owing to the decline in the temperatures realized in the cylinder [25]. For P10 fuel, CO emission was observed to be 0.037% at the load of 25%, while this value was increased to 0.101% at the maximum load. CO emission ascended with the increase in the load. Sönmez and Safa [26] reported that maximum CO emissions were measured as 0.111% for pure DF, 0.128% for P10, and 0.147% for P20 at full load conditions. The researchers found that the infusion of pyrolytic fuel increased CO emissions at all loads.

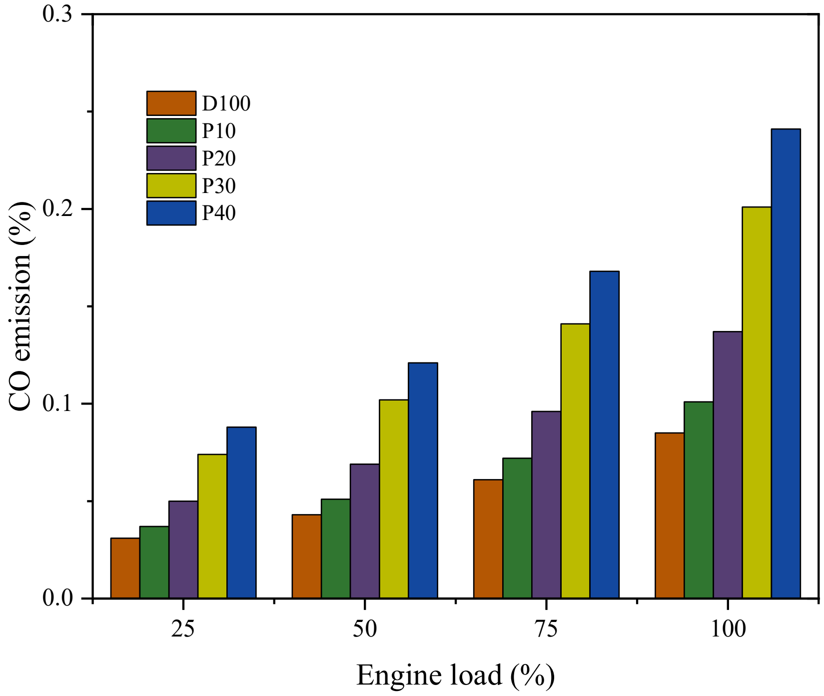


Figure 5. Load-dependent change in CO emissions for test fuels

3.5. Oxygen (O_2) Emission

The presence of oxygen in the products of combustion reactions is an important feature that gives information about the conditions of combustion process. The variation of O_2 emission values depending on load was plotted in Figure 6. As observed, insignificant reductions were observed in the amount of O_2 emission emitted as the pyrolysis oil ratio of the fuel blends increased. When the load was adjusted to 50%, the amount of O_2 released in P10 fuel was 10.22% while it was 9.3% in P40 fuel. In the tests performed with the same fuel at different loads, it was seen that the amount of O_2 decreased as the load increased. The amount of O_2 in P40 fuel decreased from 14.1% when the load was 25% to 2.62% when the load was 100%.

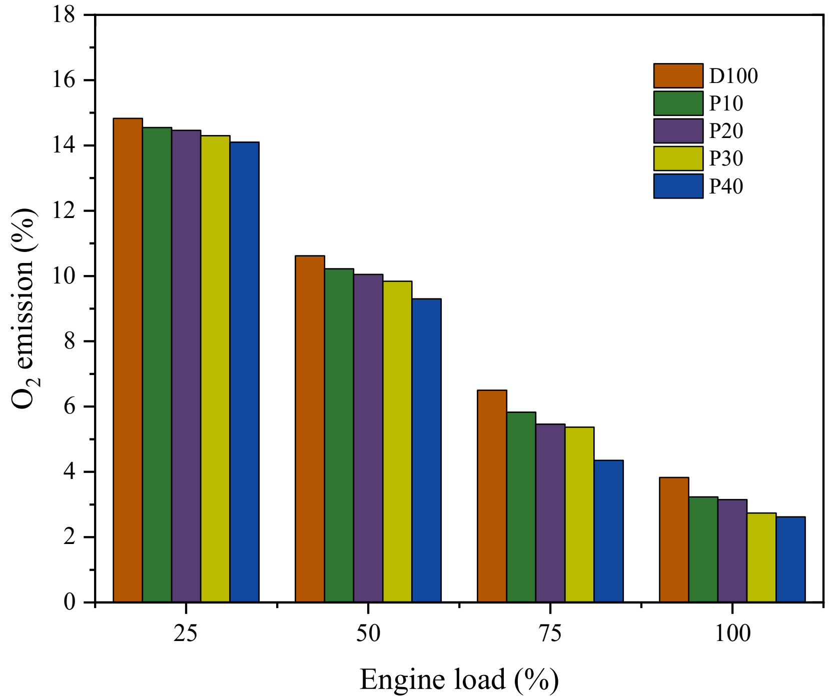


Figure 6. Load-dependent change in O_2 emissions for test fuels

3.6. Carbon Dioxide (CO_2) Emission

Figure 7 illustrates the CO_2 emissions of the test fuels used in the study at different loads. It was seen that CO_2 formation was low when loads were low. In their experimental study, Kalargaris et al. [27] emphasized that CO_2 emissions ascended with increasing pyrolysis oil ratio in the fuel blend. The researchers attributed this fact to the increase in the C/H ratio. As the load ascended, it was determined that the CO_2 emission value in pyrolysis oil-DF blends was higher than DF. At 25% load, the increase in CO_2 emission from D100 fuel to P40 fuel was 38.67%, while this case was 59.5% at 100% load.

The amount of CO_2 emitted to the atmosphere by the fuel blends used in the study for one month was calculated. In this calculation, it is assumed that the test engine runs 10 hours a day and 30 days a month. Considering the amount of harmful emissions released from the engine to the atmosphere, it is seen that pyrolysis oil/DF blends are higher than DF. However, there are many industrial applications of scrapped tyres, especially their use as fuel in cement factories. As a result of these applications, the pollutants emitted from the scrap of EOL tyres will be higher than the use as fuel. In addition, fires, insects, water and soil pollution caused by scrapped tyres should also be evaluated. As a result, the process of converting waste tyres into fuel, which is one of the steps to be taken to reduce the damage caused by waste tyres to nature at a certain level, is valuable.

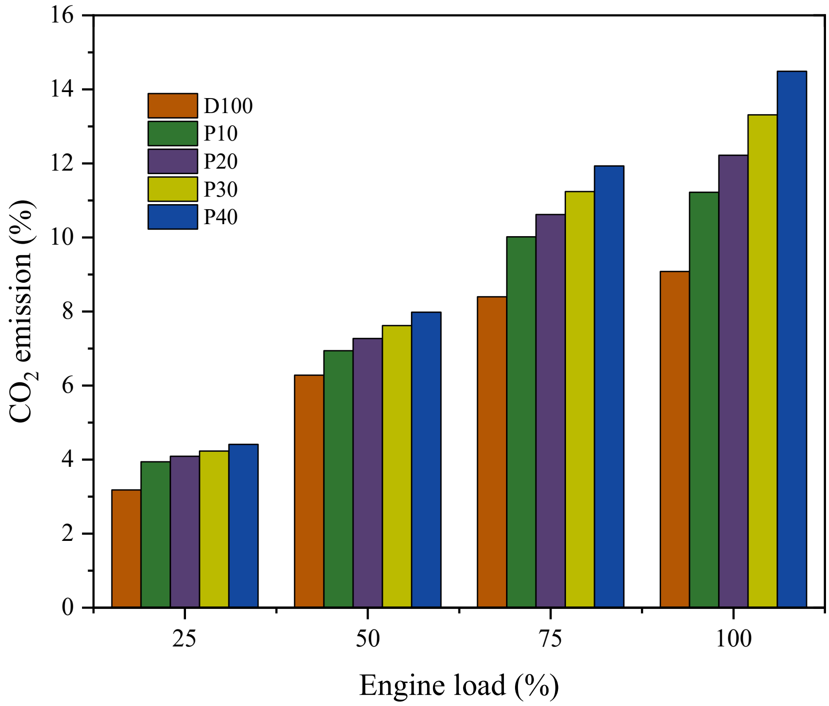


Figure 7. Load-dependent change in CO_2 emissions for test fuels

Table 4. Monthly kg CO_2 emission amount of fuel blends

	Engine Load (%)			
Test fuel	%25	%50	%75	%100
D100	948.46	3120.61	5290.96	6178.31
P10	1196.07	3534.24	6630.93	7861.31
P20	1259.52	3821.72	7181.07	8702.74
P30	1304.48	4161.40	7845.15	9397.65
P40	1365.70	4472.72	8423.29	10910.35

4. CONCLUSIONS

The use of waste tyres, which have the potential to pollute the environment, as an alternative fuel is considerable for the protection of the environment and living life. The goal of the present work is to determine the influence of WTPO on the performance and emission behaviors of a CI engine. The lesser energy content of the fuels is the most important parameter occurring the fuel consumption. In the experiments, it was pointed out that as the amount of WTPO ascended in the blends used in the experiments, the fuel consumption ascended in direct proportion. At the same loads, approximately 6.94% more fuel consumption was realized in P40 fuel as compared to D100 fuel. When studies in the literature are examined, it is seen that the oil produced from waste tyres is suitable for use in diesel engines, but it increases fuel consumption and CO_2 emissions.It was highlighted that there was an increase in emission values owing to the increase in the pyrolysis oil percentages in the blends. At the same load, HC emission increased by 13.3% as the pyrolysis oil ratio in the fuel mixture increased. The formation of CO_2 and CO emissions varies depending on the pressure and air in the cylinder. Emissions are directly proportional to both load and pyrolysis oil content. EGT increased with increasing load. However, considering that pyrolysis oil is a highly volatile fuel, the increase in pyrolysis oil in the blend led to a decrease in EGT because of its heat absorption feature. The highest EGT of the engine at full load was measured to be 606.4ºC for D100 fuel and the lowest was found as 558.5ºC for P40 fuel. Based on the findings of the study and literature survey, it was determined that WTPO can be used as an alternative fuel in diesel engines.

ACKNOWLEDGMENT

The present study has been supported by The Scientific and Technological Research Council of Turkey (TUBITAK) during the 2209A-2022/1 period (University Students Domestic Research Projects Support Program) working on projects numbered 1919B012202159.

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Talha Ertürk, Ahmet Arslan: Literature review, Resources, Experiments, Evaluation and interpretation of the results, Writing- reviewing-editing of the paper.

Erdal Tunçer: Literature review, Experiments, Resources, Writing- reviewing-editing of the paper.

Battal Doğan: Supervision, Literature review, Experiments, Resources, Drawing graphs, Evaluation and interpretation of the results, Writing- reviewing-editing of the paper.

Murat Kadir Yeşilyurt: Literature review, Drawing graphs, Evaluation and interpretation of the results, Writing- reviewing-editing of the paper.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] Rowhani A, Rainey TJ. Scrap tyre management pathways and their use as a fuel-A review. Energies 2016; 9(11): 888.

[2] Eryılmaz H, Demirarslan KO. Ömrünü tamamlamış lastiklerin (ÖTL) sıvılaştırılarak geri dönüşümünün araştırılması. Sürdürülebilir Mühendislik Uygulamaları ve Teknolojik Gelişmeler Dergisi 2019; 2(1): 50-56.

[3] Şimşek S. Pirolize edilmiş lastik yağı kullanılarak elde edilen yakıtın tek silindirli dizel motor performans ve emisyonlara etkisi. Uluslararası Yakıtlar Yanma ve Yangın Dergisi 2020; 8: 28-36.

[4] Hürdoğan E, Ozalp C, Kara O, Ozcanli M. Experimental investigation on performance and emission characteristics of waste tire pyrolysis oil–diesel blends in a diesel engine. International Journal of Hydrogen Energy 2017; 42(36): 23373-23378.

[5] Uçar M. Dizel motorlarda atık taşıt lastiklerinden elde edilen pirolitik yağın yanma ve emisyon karakteristiklerine etkilerinin deneysel ve sayısal olarak incelenmesi. Fırat Üniversitesi Fen Bilimleri Enstitüsü Otomotiv Mühendisliği Ana Bilim Dalı, Elazığ, Türkiye, 2017.

[6] Uslu S. Atık lastik piroliz yağı ile çalışan bir dizel motorda emisyon ve performansın eşzamanlı tahminine yönelik bir cevap yüzey metodunun geliştirilmesi. Düzce Üniversitesi Bilim ve Teknoloji Dergisi 2019; 7(3): 1261-1278.

[7] Umeki ER, de Oliveira CF, Torres RB, dos Santos RG. Physico-chemistry properties of fuel blends composed of diesel and tire pyrolysis oil. Fuel 2016; 185: 236-242.

[8] Karagöz M, Ağbulut Ü, Sarıdemir S. Waste to energy: Production of waste tire pyrolysis oil and comprehensive analysis of its usability in diesel engines. Fuel 2020; 275: 117844.

[9] Yaqoob H, Teoh YH, Jamil MA, Sher F. Energy, exergy, thermoeconomic and sustainability assessment of tire pyrolysis oil in common rail direct injection diesel engine. Fuel 2022; 311: 122622.

[10] Karagöz M, Uysal C, Ağbulut Ü, Sarıdemir S. Energy, exergy, economic and sustainability assessments of a compression ignition diesel engine fueled with tire pyrolytic oil-diesel blends. Journal of Cleaner Production 2020; 264: 121724.

[11] Uzun S. Dizel bir motorda atık lastikten elde edilen pirolitik yakıtın motor performans ve emisyonlarına etkisi. Karabük Üniversitesi Lisansüstü Eğitim Enstitüsü Makine Mühendisliği Ana Bilim Dalı, Karabük, Türkiye, 2020.

[12] Martínez JD, Puy N, Murillo R, García T, Navarro MV, Mastral AM. Waste tyre pyrolysis-A review. Renewable and Sustainable Energy Reviews 2013; 23: 179-213.

[13] Zhang G, Chen F, Zhang Y, Zhao L, Chen J, Cao L, Gao J, Xu C. Properties and utilization of waste tire pyrolysis oil: A mini review. Fuel Processing Technology 2021; 211: 106582.

[14] İlkılıç C, Aydın H. Fuel production from waste vehicle tires by catalytic pyrolysis and its application in a diesel engine. Fuel Processing Technology 2011; 92(5): 1129–1135.

[15] Martínez JD, Rodríguez-Fernández J, Sánchez-Valdepeñas J, Murillo R, García T. Performance and emissions of an automotive diesel engine using a tire pyrolysis liquid blend. Fuel 2014; 115: 490-499.

[16] Lewandowski WM, Januszewicz K, Kosakowski W. Efficiency and proportions of waste tyre pyrolysis products depending on the reactor type-A review. Journal of Analytical and Applied Pyrolysis 2019; 140: 25-53.

[17] Kumaravel ST, Murugesan A, Kumaravel A. Tyre pyrolysis oil as an alternative fuel for diesel engines-A review. Renewable and Sustainable Energy Reviews 2016; 60: 1678-1685.

[18] Wang WC, Bai CJ, Lin CT, Prakash S. Alternative fuel produced from thermal pyrolysis of waste tires and its use in a DI diesel engine. Applied Thermal Engineering 2016; 93: 330-338.

[19] Ruwona W, Danha G, Muzenda E. A review on material and energy recovery from waste tyres. Procedia Manufacturing 2019; 35: 216-222.

[20] Yaqoob H, Teoh YH, Sher F, Jamil MA, Ali M, Ağbulut Ü, Salam HA, Arslan M, Soudagar MEM, Mujtaba MA, Elfasakhany A, Afzal A. Energy, exergy, sustainability and economic analysis of waste tire pyrolysis oil blends with different nanoparticle additives in spark ignition engine. Energy 2022; 251: 123697.

[21] İsmailoğlu E. Pirolize atık lastik yağı-motorin karışımının common-rail direkt enjeksiyonlu bir dizel motorda kullanımı. Kocaeli Üniversitesi Fen Bilimleri Enstitüsü Otomotiv Mühendisliği Ana Bilim Dalı, Kocaeli, Türkiye, 2021.

[22] Hall D. Automotive Engineering. Delhi, India: Global Media, 2008.

[23] Murugan S, Ramaswamy MC, Nagarajan G. A comparative study on the performance, emission and combustion studies of a DI diesel engine using distilled tyre pyrolysis oil–diesel blends. Fuel 2008; 87(10-11): 2111-2121.

[24] Frigo S, Seggiani M, Puccini M, Vitolo S. Liquid fuel production from waste tyre pyrolysis and its utilisation in a diesel engine. Fuel 2014; 116: 399-408.

[25] Doğan O, Celik MB, Özdalyan B. The effect of tire derived fuel/diesel fuel blends utilization on diesel engine performance and emissions. Fuel 2012; 95: 340-346.

[26] Sönmez Hİ, Safa A. Pirolitik yakıtın dizel motor performansı ve emisyonlarına etkisi. 1st International Conference on Trends in Advanced Research ICTAR 2023, 279-285, Konya, Türkiye, 2023.

[27] Kalargaris I, Tian G, Gu S. Combustion, performance and emission analysis of a DI diesel engine using plastic pyrolysis oil. Fuel Processing Technology 2017; 157: 108-115.