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Original Research Article

From waste to clean energy: multi-objective optimization of engine efficiency and emissions using waste plastic oil

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ABSTRACT

Plastics are used in a wide variety of industries due to their advantages such as being light, flexible, and easy to shape. Today, the use of plastics is increasing every year due to the increasing consumption frenzy. Although the average lifespan of plastics is approximately 10 years, it takes years for them to decompose in nature on their own. In this study, the potential of converting waste plastic cables into oil was investigated, and the effects of blending this oil with diesel on engine performance and emissions were evaluated. The aim is to offer an alternative solution to the environmental problems caused by increasing plastic waste and fossil fuel dependence. To create test fuels, the generated oil was combined with diesel fuel in three distinct volumetric ratios (10%, 20%, and 30%). A 4-stroke, air-cooled, single-cylinder diesel engine was used to test these test fuels at a constant speed of 3000 rpm while under six distinct loads (0.5, 1, 1.5, 2, 2.5, and 3 kW). Utilizing the data from the studies utilizing the response surface methodology (RSM), the ideal engine load was 1.5 kW, and the ideal waste plastic oil ratio was 14%. Under ideal conditions, brake thermal efficiency (BTE) was determined to be 23.17%, brake specific fuel consumption (BSFC) to be 371.48 g/kWh, nitrogen oxide (NO_x) to be 495.96, carbon dioxide (CO_2) to be 5.29%, hydrocarbon (HC) to be 21.93 ppm, and carbon monoxide (CO) to be 0.049%. In the optimization study, the lowest correlation coefficient (R^2) value belongs to CO with 97.43%. The highest error rate belongs to CO with 5.69%, and the lowest error rate belongs to HC emission with 0.99%. Oil extracted from used plastic cables has been found to be useful when combined with diesel. RSM has been effectively used, exhibiting high R^2 values and low error rates.

Keywords: Diesel engine, Waste to energy, RSM, Waste Plastic Oil

1. Introduction

Due to its many benefits, including efficiency, longevity, and low fuel consumption, diesel engines are now commonly chosen in a variety of industries, transportation, and agriculture, as well as in many power production devices [1]. Diesel engines run on diesel fuel derived from fossil fuels. The fact that fossil fuel deposits are located in certain areas, that their value fluctuates based on political situations and reserve size, and that their value is continuously declining are some of their drawbacks [2]. In addition, as a result of burning fossil fuels, harmful emissions such as CO_2, NO_x, CO, and HC are released for humans and the environment [3,4]. Researchers have started to search for new fuels in order to prevent these disadvantages of fossil fuels and to ensure energy sustainability. Researchers have tried various fuels such as various alcohols [5], biogases [6], hydrogen [7], and biofuels [8]. Because of their physical and chemical similarities to diesel fuel and their capacity to be used in diesel engines without requiring a 20% mixture alteration, biofuels have been widely chosen among these fuels [9,10]. Waste oils, animal fats, vegetable oils, and microalgae are just a few of the raw resources that can be used to make biofuels [11,12]. One of the waste oils is the oils obtained from waste plastics. Plastics are frequently used today thanks to their advantages such as being flexible, easy to shape, and lightweight [13]. With the increasing consumption frenzy today, the amount of plastics used for different purposes is increasing day by day. In 2012, 280 million metric tons (MMT) [14] reached 368 MMT in 2019 [15] and approximately 400 MMT in 2022 [16]. According to estimates, it is expected to reach 500 MMT by 2050 [15]. Although the shelf life of plastics is an average of 10 years [17], plastics can remain intact in nature for thousands of years depending on climate conditions [18]. Disposing of plastics in soil and water endangers ecological and living life [19]. As a result of burning unrecyclable plastics, emissions such as furan and mercury, which are harmful to the human healt and environment, are released [20]. In studies, the recycling of plastics through pyrolysis and the usability of these waste plastics as fuel have been accepted as a solution. Plastic waste is considered a good alternative fuel because it contains approximately 41- 47 MJ/kg of energy [21]. Recycling plastics and avoiding the drawbacks of diesel fuel are made possible by the generation of gasoline from plastic waste. In one of the studies conducted within this scope, Kalargaris et al. [22] investigated the effects of oils produced at different pyrolysis temperatures (700 and 900 °C) on diesel engines. Diesel, plastic pyrolysis oil generated at 700, plastic pyrolysis oil produced at 900 °C, and fuels made by adding 25% diesel by volume were all used in the study. The engine was run in the study at a constant speed of 1500 rpm while being subjected to three distinct loads: 75%, 85%, and 100%. In comparison to the fuel obtained at 700 degrees, they discovered that the fuel acquired at 900 degrees had a larger heat release rate, a shorter combustion period, and a longer ignition delay. They discovered that the gasoline obtained at 700 degrees had a BTE value that was 2-3% lower than the fuel acquired at 900 degrees, and the BTE value was 3-4% lower. The highest emission values were determined in the fuel obtained at 900 degrees. Venkatesan et al. [23] assessed the fuels' engine performance and emission characteristics at full load and no load by combining 15% and 30% diesel by volume with biodiesel made from waste plastic oil. They concluded from the experiment that the high calorific value of plastic oils contributed to an improvement in the BTE value. They found that for all test fuels, BSFC dropped as load increased. When biodiesel was added, they noticed an increase in CO, HC, smoke, and NO_x emissions. Kumar et al. [24] extracted waste oil from waste high density polyethylene by catalytic pyrolysis. They mixed this fuel they obtained with diesel at 10%, 20%, 30%, and 40% by volume and conducted engine tests. They observed that BTE decreased while BSFC increased due to the low calorific value of the waste oil. They determined that although CO, HC and NO_x increased as the biodiesel ratio increased, CO_2 emissions were lower than diesel in almost all mixtures. In the studies, it was observed that experiments were carried out by mixing different biodiesels obtained from waste pyrolysis oil with diesel in various ratios. However, it was observed that the experiments of intermediate values in the mixtures were not carried out, and their effects could not be determined. Experiments at intermediate values cannot be carried out due to reasons such as the need for too much time and the cost of the experiments. Up to a certain point, the additional biodiesel ratio improves performance, emissions, and combustion. But it has a negative effect after a certain value due to reasons such as increasing viscosity, density, and low calorific value [25–27].

There are a lot of studies on using waste as fuel, as the literature shows. To find the best biodiesel ratio, several research is now doing optimization experiments. In the optimization study, techniques such as RSM [28], Taguchi [29], and artificial neural networks (ANN) [30] are generally used. In one of the studies carried out in this context, Simsek and Uslu [31] optimized biodiesel and diesel mixtures obtained from safflower, waste vegetable oil, and canola oils with RSM. Exhaust gas temperature, BTE, smoke, NO_x, and CO_2 were identified as output parameters in the study, while the biodiesel ratio, engine load, and injection pressure were identified as input parameters. In the study, they carried out an optimization study by targeting maximum values for BTE and minimum values for all other output parameters. The study's ideal parameters were found to be 1484.85 W engine load, 215.56 bar injection pressure, and a 25.80% biodiesel ratio. In these study conditions, BTE was found as 20.54%, EGT as 199.88 ℃, smoke as 0.26%, NO_x as 558.44 ppm, and CO_2 as 4.52%. It was determined that the optimization study had an acceptable error rate and was successfully implemented. In another study, Kumar and Dinesha [32] performed engine parameter optimization with RSM using methyl ester biodiesel. NO_x and BTE were identified as the study's outcome characteristics, while engine load, compression ratio, biodiesel ratio, and injection timing were identified as input parameters. The study found that 86.63% engine load, 15% biodiesel ratio, 16 compression ratio, and 26.24 ^{o}BTDC injection time were the ideal operating conditions. In these operating conditions, NO_x was determined as 220.64 ppm and BTE as 31.5%. In another study, Dubey et al. [33] investigated the impact of combining waste cooking soybean oil biodiesel with diesel on engine performance and emissions. The study's input parameters were engine load, exhaust gas recirculation quantity, and biodiesel ratio. The output metrics that were identified were smoke, NO_x, CO, HC, BTE, and BSFC. They conducted an optimization study by targeting maximum value for BTE and minimum value for BSFC and emissions. In the study, it was determined that the R^2 value of all output parameters was above 99%, and all error rates were below 6%.

It is seen in the literature that biodiesel/diesel blends are optimized under various conditions. Nevertheless, no research on the optimization of waste plastic oil/diesel fuel blends made from waste cable plastics has been discovered. This study was conducted to address the increasing energy demand through waste control, a significant environmental issue today. Waste plastic oil was produced using waste cable plastics, and this oil was mixed with diesel at three different ratios: 10%, 20%, and 30% by volume. The resulting test fuels were tested at six different loads, starting from 0.5 kW to 3 kW, and engine performance and emission values were measured during these tests. Finally, the data obtained from the experimental study was optimized using RSM to determine the optimum mixing ratio and engine load that yielded minimum emissions and maximum performance. This study comprehensively investigated the impact of waste plastic oil obtained from waste cable plastic on engine performance and emissions.

2. Materials and Methods

In the study, by mixing waste plastic oil obtained from waste cable plastic with diesel in 3 different ratios by volume, D100W0 (100% Diesel), D90W10 (90% Diesel + 10% Waste plastic oil), D80W20 (80% Diesel + 20% Waste plastic oil), and D70W30 (70% Diesel + 30% Waste plastic oil) test fuels were obtained. The test fuels were tested in a diesel engine at 3000 rpm constant speed and 6 different loads (between 0.5 kW and 3 kW). The data obtained as a result of the experimental study will be used for optimization with RSM, and the optimum operating conditions will be determined.

In the pyrolysis unit shown in Figure 1, the catalytic pyrolysis method was used to obtain waste cable plastic oil. Before starting the process, the out-of-service cables, which are found in the outer coating of the electric cables and increase their durability, were subjected to various pre-treatment steps such as washing, shredding, grinding, cutting, breaking, and

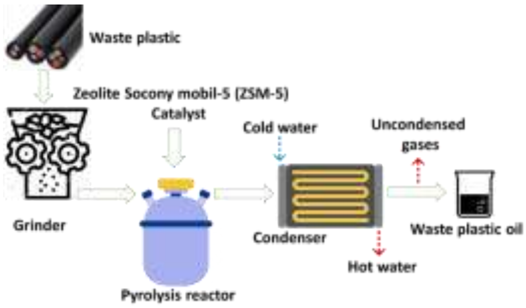

Figure 1. Waste plastic oil production

shearing. As a result of these processes, the cables were separated into small pieces ranging from 5 to 50 mm. 10% coal by weight and 1% catalyst were added to the chamber along with the manufactured plastic substance. After that, the mixture was moved to the reactor for the pyrolysis process, which took place in an inert, restricted, and oxygen-free environment. The proportional-integral-derivative controller was used to maintain a steady reactor temperature between 450 and 500 °C at atmospheric pressure and the heating rate was approximately 10 °C/min. The pyrolysis process was left to run for four to five hours after the temperature was attained. After that, water was used to condense the plastic vapor in a double-walled condenser. After being gathered by weight in a tank, the condensed liquid was cleaned and prepared for use. Table 1 displays the technical parameters of the fuels. To evaluate the feasibility of using waste plastic oil derived from waste cable plastic in diesel engines, the following production and experimental procedures were carried out.

An air-cooled, single-cylinder, 4-stroke Lutian 3GF-ME diesel engine was used for the trials. Table 2 displays experimental setup and engine technical specifications. By inserting the emission device's probe into an exhaust line channel opening, emissions were monitored. All measurement tools were calibrated before to the tests. The engine was operated for approximately 30 minutes at no load in order to reach thermal equilibrium. After reaching thermal equilibrium, the engine was loaded starting from a load of 0.5 kW and increasing by 0.5 kW up to a load of 3 kW. To ensure accuracy and repeatability, every experiment was conducted three times. To ensure that no test fuel was left in the system, the engine was run on pure diesel fuel for ten minutes at the conclusion of the testing. Figure 2 displays a schematic illustration of the engine test setup. The Kline and McClintock approach (equation 1) was used to calculate the measured values' uncertainty. [34]. CO, HC, NO_x, CO_2, BSFC, BTE, and load have uncertainty values of ±1.5, ±1.1, ±2.3, ±1.5, ±0.8, ±0.7, and ±0.6, respectively. It is found that the overall uncertainty is ±3.53%.

$$\sqrt{\begin{matrix}[(U_{CO})^2 + (U_{HC})^2 + (U_{Load})^2 + (U_{BTE})^2 \\ +(U_{BSFC})^2 + (U_{CO_2})^2 + (U_{NO_x})^2]\end{matrix}} \quad (1)$$

Table 2. Experimental setup and engine technical specifications

Engine Model	Lutian 3GF-ME	
Cooling Type	Air Cooled	
Number of Cylinder	Single	
Rating Speed	3000 rpm	
Rated power	3.2 kW	
Swept Volume	296 cm^3	
Emission device model	**MOD 2210 WINXP-K**	
Parameter	Sensibility	Measurement Range
CO_2	0.01%	0 - 20% vol
NO_x	± 1 ppm	0-5000 ppm
CO	0.01%	0 - 10% vol
HC	± 1 ppm	0-10000 ppm

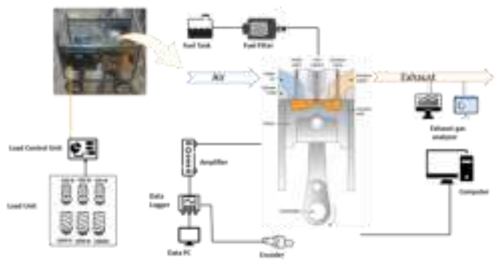

Figure 2. Schematic representation of the engine test setup

Because experimental research is expensive and time-consuming, determining intermediate values is difficult. ANN, RSM, and Taguchi optimization approaches are used to solve this problem and determine the optimal process conditions [35,36].

Table 1. Characteristics of test fuels

Property	Waste plastic oil	Diesel	D90W10	D80W20	D70W30
Cetane no.	48	53.4	52.9	52.3	51.8
Calorific value (MJ/kg)	42.5	43.2	43.1	43	42.9
Density (Kg/m^3)	778	830	825	820	814
Kinematic Viscosity (mm^2 /s)	0.96	4.24	3.81	3.38	2.95

Table 3. Factor levels

Factors	Levels					
Waste plastic oil ratio (%)	0	10	20	30	-	-
Load (W)	500	1000	1500	2000	2500	3000

Table 4. Experimental Desing

Blend (%)	Load (kW)	CO (%)	HC (ppm)	CO_2 (%)	NO_x (ppm)	BSFC (g/kWh)	BTE (%)
0	0.5	0.105	12.33333	3.424	241.6667	654.5455	12.73148
0	2	0.061	39.33333	5.608	577.3333	297.931	27.97068
0	3	0.081	60	7.644	780.6667	337.5	24.69136
10	0.5	0.098	4	3.744	287	771.4286	10.80247
10	1.5	0.057	24.33333	5.312	473.3333	363.6364	22.91667
10	2.5	0.045333	42.33333	7.172	696	291.5385	28.58399
10	3	0.067	49	8.376	800	309.6774	26.90972
20	1	0.057	13.33333	4.508	390.3333	488.3636	17.06379
20	1.5	0.045667	22	5.288	493.6667	384	21.70139
20	2.5	0.035	40	7.164	728.3333	297.931	27.97068
30	0.5	0.082333	12.66667	3.748	253.6667	800	10.41667
30	1.5	0.047667	32	5.26	452.6667	400	20.83333
30	2	0.037667	41	6.224	584.6667	317.6471	26.23457
30	2.5	0.037667	48.33333	7.296	664.3333	325.1613	25.62831

Because of its benefits, which include fewer tests, a low error rate, data visualization, and the capacity to ascertain the impact of independent factors on replies, RSM stands out among these methodologies [37,38]. It offers numerous benefits, particularly when it comes to complex system optimization. In addition to enhancing existing systems, RSM can serve as a guidance method while creating new ones [39]. RSM, a second-degree polynomial, models complex systems using Equation 2.

$$y = \sum_{i=1}^{k} \beta_i x_i + \varepsilon + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \beta_0 \quad (2)$$

The β coefficient denotes the expected response (y), the regression coefficients (β_i and β_j), the order of the model (k), the constant (β_0), the random error (ε), and the individual variables (x_i and x_j).

The optimization study was carried out with a Two-Level Factorial (Central Composite Design) and a 95% confidence interval. Finding the ideal operating parameters that yield the lowest emission and BSFC value and the maximum BTE value based on the engine load and the ratio of waste plastic oil added to diesel was the study's goal. Table 3 displays the engine load levels and waste plastic oil ratio that are acceptable as inputs. Table 4 shows the experimental design table.

3. Results and Discussion

The amount of fuel-derived power that is transformed into usable work is indicated by the BTE value. As the in-cylinder temperature rose in response to an increasing load, combustion improved, and the BTE value rose for all test fuels. The BTE value dropped after a particular load since there wasn't enough time for full combustion. The BTE surface and contour graphs are displayed in Figure 3. In the tests, the D70W30 fuel had the lowest BTE value (10.42%) with a 0.5 kW load, while the D90W10 fuel had the greatest BTE value (28.70%) at a 2 kW load. The average BTE value decreased by 5.82%, 7.93%, and 13.61% for D90W10, D80W20, and D70W30 fuels, respectively, compared to D100W0 fuel. When the graphs are examined, a decrease in BTE value occurred with the increase in the amount of waste plastic oil added. As in the studies of Rajaraman et al. [40] and Rao et al. [41], fuel consumption increases due to the low calorific value, and the BTE value decreases due to this increase. The highest BTE value is observed at approximately 2 kW load and in the 0-10% blend range.

The BSFC unit, one of the performance metrics, is g/kWh. It shows the amount of fuel required

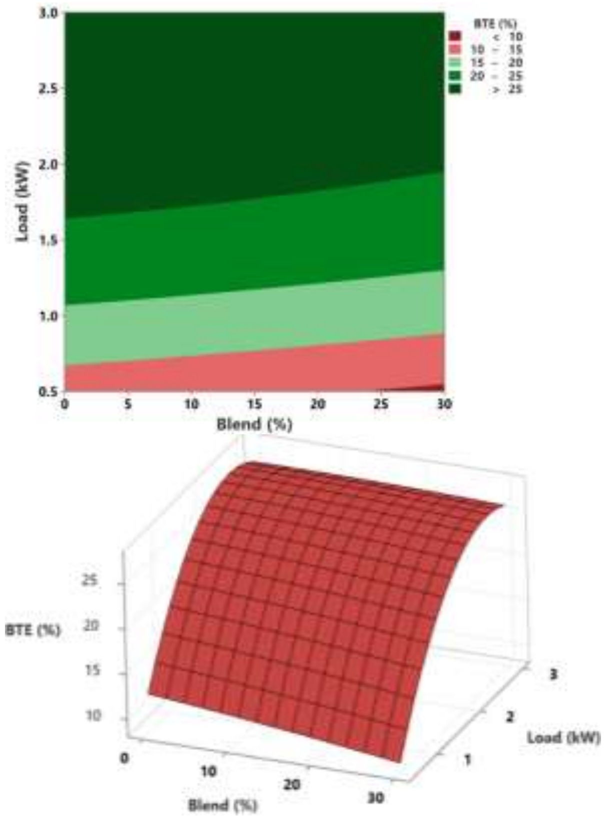

Figure 3. BTE varies with load and waste plastic oil ratio.

in an hour to produce 1 kW of power, expressed in grams. Figure 4 shows contour and surface plots showing how waste plastic oil amount and engine load affect BSFC. All test fuels showed a drop in BSFC up to a specific load, but after that, the BSFC number rose since there was not enough time for full combustion [42]. The D70W30 fuel had the highest BSFC value of 800 g/kWh at 0.5 kW load, while the D90W10 fuel had the lowest BSFC value of 290.32 g/kWh at 2 kW load. The average BSFC value for D90W10, D80W20, and D70W30 fuels rose by 7.65%, 10.02%, and 16.82%, respectively, in comparison to D100W0 fuel. Because biodiesels have lower calorific values than diesel fuel, they use more fuel to generate the same amount of power, according to research by Srithar et al. [43] and Venkatesan et al. [44]. The lowest BSFC value is displayed in Figure 4 with a 0–10% waste plastic oil blend and a load of about 2 kW.

When ambient nitrogen and oxygen combine during high-temperature combustion in the engine, NO_x emissions, which are extremely detrimental to the environment, are created. The contour and surface graphs in Figure 5 illustrate the relationship between NO_x emissions and engine load and the amount of waste plastic oil

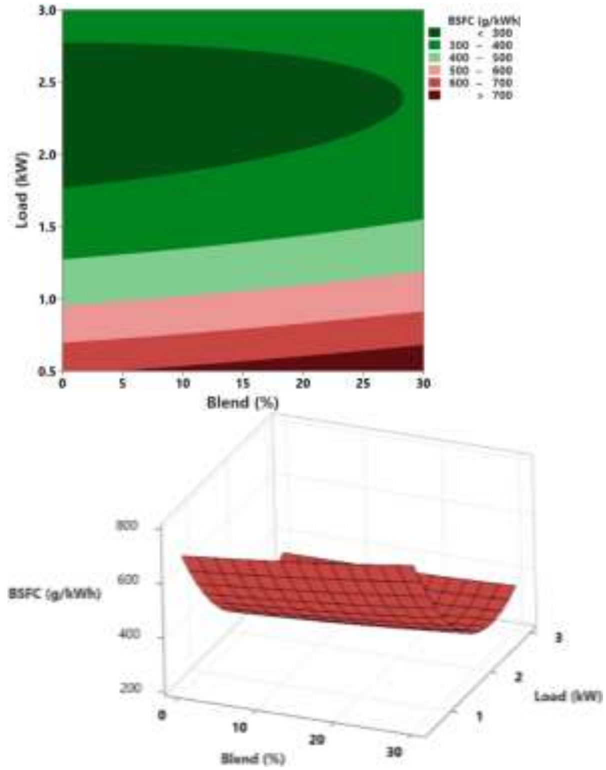

Figure 4. BSFC varies with load and waste plastic oil ratio.

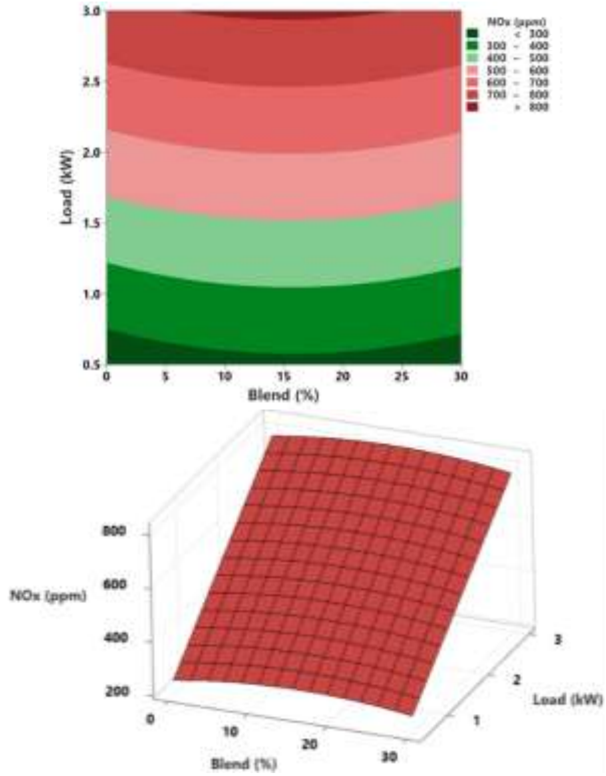

Figure 5. NO_x varies with load and waste plastic oil ratio.

used. The D80W20 fuel had the greatest NO_x value, 819 ppm, at a 3 kW load, while the D100W0 fuel had the lowest NO_x value, 242 ppm, at a 0.5 kW load. In all test fuels, NO_x emissions rose as load increased because they rose in tandem with increases in in-cylinder temperature and pressure [45]. The higher oxygen content of biodiesel compared to fossil diesel increased the rate of complete combustion, and with the increased combustion rate, the in-cylinder temperature increased, which in turn increased NO_x emissions [46]. However, as the proportion of biodiesel in the mixture increased, combustion deteriorated, leading to a decrease in NO_x again. It is believed that the low volatility of biodiesel hinders atomization, slowing combustion speeds and limiting maximum temperatures, thus reducing NO_x formation [47]. Compared to D100W0 fuel, the average NO_x emission values for D90W10, D80W20, and D70W30 fuels rose by 6.56%, 10.56%, and 0.05%, respectively. Figure 5 illustrates how NO_x emissions rise as load increases. For fuels containing 0–15% biodiesel, the lowest NO_x emission value was recorded at a load of about 0.5 kW.

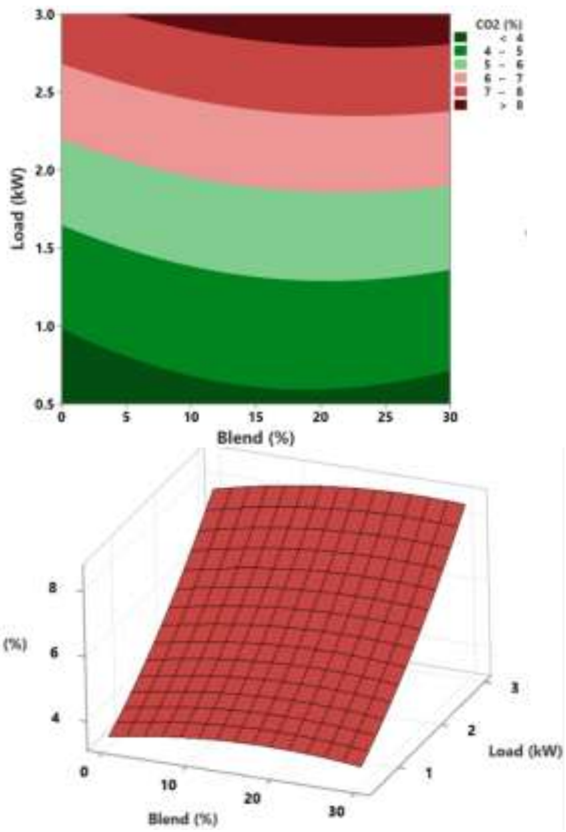

Figure 6. CO_2 varies with load and waste plastic oil ratio.

Figure 6 illustrates how CO_2 emissions vary based on the load and waste plastic oil percentage. For all test fuels, CO_2, the byproduct of full combustion, rose as the load increased. The D80W20 fuel had the greatest CO_2 emission value at 3 kW load, while the D100W0 fuel had the lowest at 3.42% at 0.5 kW load. Biodiesel increases the rate of complete combustion thanks to its high oxygen content, which increases the CO_2 emissions resulting from complete combustion. [48]. However, as the proportion of biodiesel added increases, CO_2 emissions decrease as fuel atomization deteriorates due to the high volatility of biodiesel. [49,50]. The average CO_2 emission value increased by 12.18%, 13.41%, and 12.55% for D90W10, D80W20, and D70W30 fuels, respectively, compared to D100W0 fuel. Examining Figure 6, it can be seen that the load with a CO_2 emission of 0.5 to 1 kW and 0 to 15% waste plastic oil addition has the lowest CO_2 emission value.

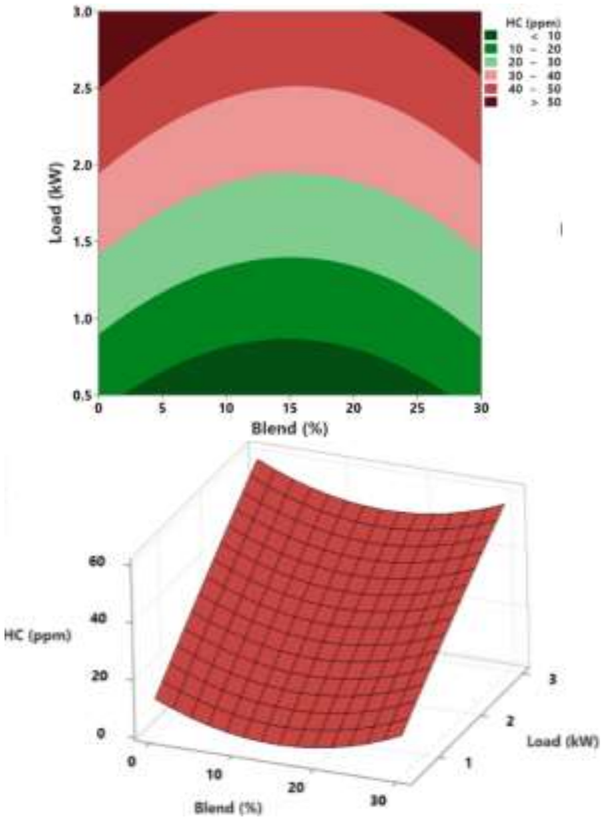

Figure 7. HC varies with load and waste plastic oil ratio.

Figure 7 displays the variation in HC emission, a byproduct of incomplete combustion, based on the load and waste plastic oil percentage. In all test fuels, HC emissions rose as the load increased. D70W30 fuel had the greatest HC emission value at 3 kW load, whereas D90W10 fuel had the lowest at 4 ppm at 0.5 kW load. While HC emissions were reduced up to a certain level with the addition of biodiesel, after a certain value, the added biodiesel worsened the combustion and increased HC emissions [51,52]. While the average HC emission value of D90W10 and D80W20 fuels decreased by 26.69% and 26.42% compared to D100W0, it increased by 5.61% for D70W30 fuel. A greater glance at Figure 7 shows that HC emissions rise as load increases. Additionally, at a load of about 0.5 kW, a fuel blend with 10–20% waste plastic oil produces the lowest HC emissions.

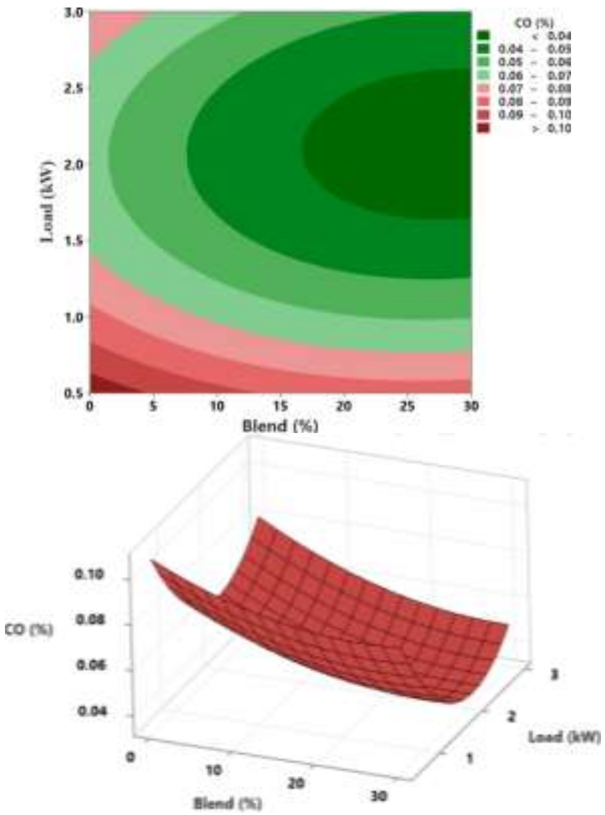

Figure 8. CO varies with load and waste plastic oil ratio.

The change of CO emission, another incomplete combustion product, according to engine load and waste plastic oil ratio, is shown in Figure 8. While CO emissions decrease up to a certain load (approximately 2.5 kW) for all test fuel types, they increase after this load due to insufficient time for homogeneous and complete combustion. When D80W20 fuel was used at a 2.5 kW load, the lowest CO emission value was 0.035%, and when D100W0 fuel was used at a 0.5 kW load, the maximum CO emission value was 0.105%. When biodiesel is added to diesel up to a specific ratio, its high oxygen content improves combustion and lowers CO emissions, but after a specific ratio, the added biodiesel increases fuel viscosity, disrupts fuel atomization, and the high oxygen content prevents homogeneous combustion [53,54]. The average CO emission value for D90W10, D80W20, and D70W30 fuels dropped by 21.78%, 39.37%, and 37.56%, respectively, in comparison to D100W0 fuel. CO emissions are high at low loads, according to an analysis of the CO emission graphs. With a 20–30% blend of waste plastic oil, the lowest CO emission levels happen at a load of about 2 kW.

The RSM analysis identified CO, HC, NO_x, CO_2, BTE, and BSFC as output parameters and the waste plastic oil ratio and engine load as input factors. The R^2 values of the output parameters were found to be 97.43% for CO, 99.72% for HC, 99.76% for CO2, 99.63% for NO_x, 97.97% for BSFC, and 97.55% for BTE. In the optimization study we conducted at a 95% confidence interval, the R^2 values of all output parameters were above 95%. Table 5 displays the regression equations that were used for predicting the output values based on the input data.

Table 5. Equations*

CO	*0.14091 – 0.001703 WP – 0.07647 EL + 0.000034 WP*WP + 0.01869 EL*EL – 0.000111 WP*EL*
HC	*1.98 – 1.237 WP + 20.55 EL + 0.04293 WP*WP - 0.504 EL*EL – 0.0399 WP*EL*
CO_2	*2.930 + 0.0474 WP + 0.840 EL – 0.001347 WP*WP + 0.2535 EL*EL + 0.00608 WP*EL*
NO_x	*138.5 + 4.81 WP + 215 EL – 0.1508 WP*WP- 0.54 EL*EL – 0.072 WP*EL*
BSFC	*961.8 + 3.20 WP - 613 EL + 0.0237 WP*WP+ 135 EL*EL – 1.148 WP*EL*
BTE	*3.63 - 0.108 WP + 19.61 EL – 0.00062 WP*WP- 4.012 EL*EL + 0.0375 WP*EL*

* WP: waste plastic oil ratio, EL: Engine load

RSM values were calculated by writing input values in the regression equations in Table 5. The error rates between the experimental data used to train the model and the data obtained as a result of the regression equation were determined. The error rates of CO and HC are displayed in Figure 9, CO_2 and NO_x are displayed in Figure 10, and the error rates of BSFC and BTE output parameters are displayed in Figure 11. The average errors were 5.69% for CO, 2.66% for HC, 0.99% for CO2, 1.72% for NO_x, 4.20% for BSFC, and 4.54% for BTE.

An optimization study was conducted with the goal of achieving the maximum value for BTE and the minimum value for all other output parameters in order to identify the ideal operating circumstances. Figure 12 displays chart for optimizing minimum emissions and maximum performance.

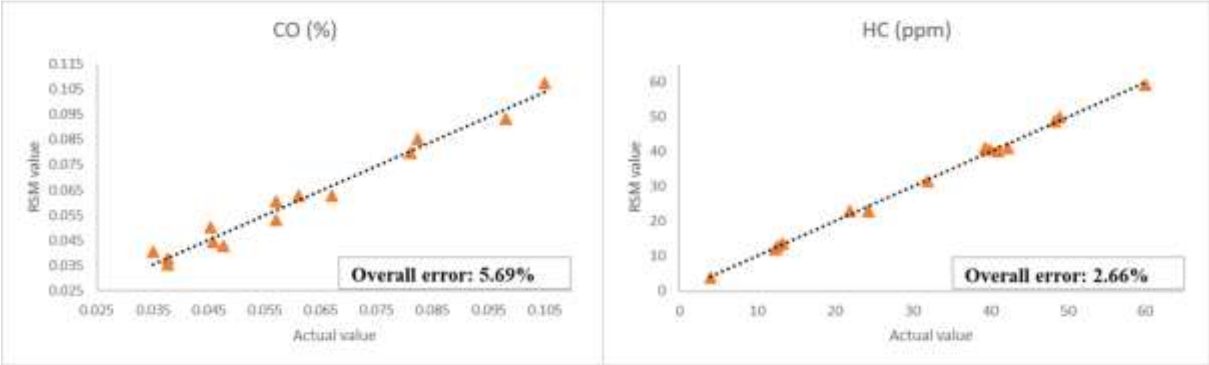

Figure 9. Error rates of CO and HC

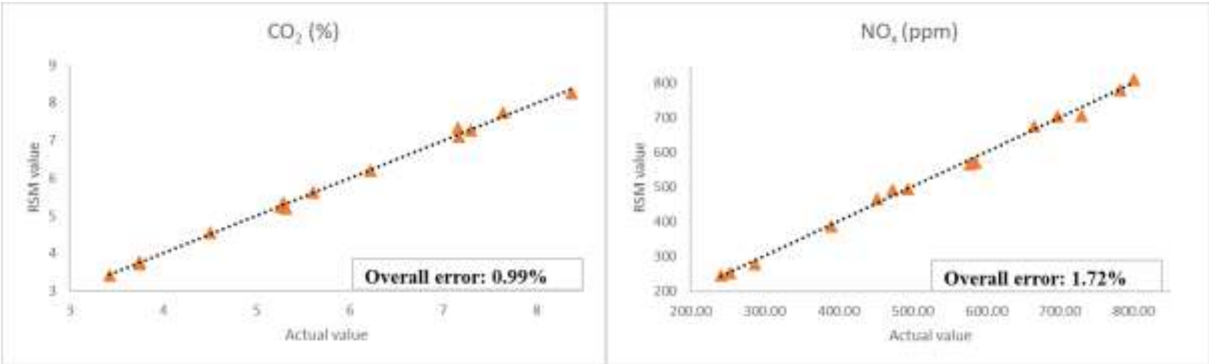

Figure 10. Error rates of CO_2 and NO_x

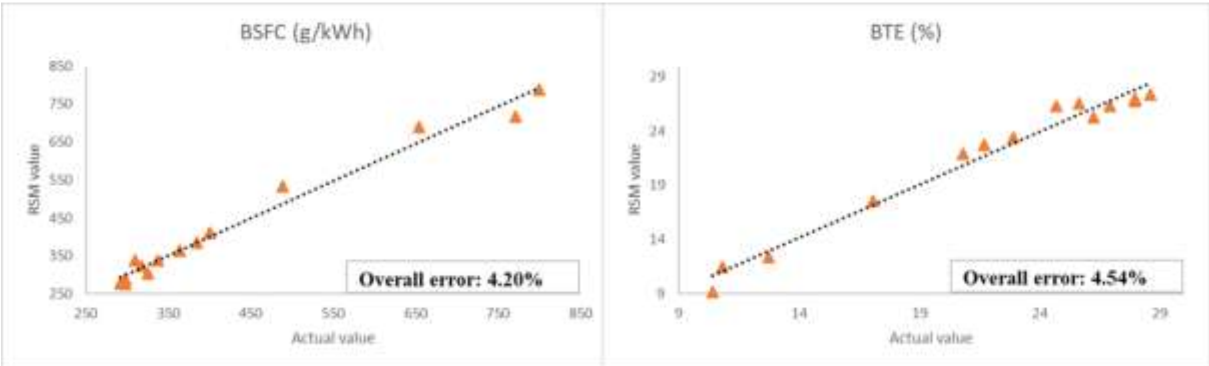

Figure 11. Error rates of BSFC and BTE

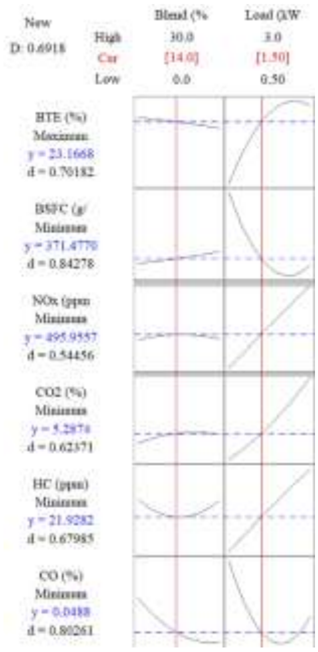

Figure 12. Chart for optimizing minimum emissions and maximum performance

Table 6. The verification error rates

	CO		CO_2		HC	
	RSM	Test	RSM	Test	RSM	Test
	0.0488	0.052	5.29	5.30	21.93	23
Error, %	**7.22**		**0.22**		**4.65**	
	NO_x		**BSFC**		**BTE**	
	RSM	Test	RSM	Test	RSM	Test
	495.96	415.65	371.48	371.78	23.17	22.43
Error, %	**3.01**		**0.08**		**3.29**	

The optimal engine load was found to be 1.5 kW, the optimal waste plastic oil ratio to be 14%, and the optimization study's desirability (D) value was found to be 0.69. Under optimum conditions, BTE was determined as 23.17%, BSFC as 371.48 g/kWh, NO_x as 495.96, CO_2 as 5.29%, HC as 21.93 ppm, and CO as 0.049%. To verify the obtained results, another test was carried out under optimum operating conditions. Table 6 shows the RSM and test values under optimum operating conditions and the error rates between them. The highest mistake rate in CO emission was 7.22%, whereas the lowest error rate in BSFC was 0.08%. With all error rates under 10%, the optimization research was completed successfully.

4. Conclusion

This study examined the impact on engine performance and emissions of test fuels made by combining diesel and waste plastic oil made from waste cable plastic at three different volumetric ratios (10%, 20%, and 30%). The information gathered from the experimental investigation was used to identify ideal operating conditions.

✓ When D80W20 fuel was used at a 2.5 kW load, the lowest CO emission value was 0.035%, and when D100W0 fuel was used at a 0.5 kW load, the maximum CO emission value was 0.105%. The average CO emission value for D90W10, D80W20, and D70W30 fuels dropped by 21.78%, 39.37%, and 37.56%, respectively, in comparison to D100W0 fuel.

✓ At 3 kW load, D70W30 fuel had the highest HC emission value, whereas at 0.5 kW load, D90W10 fuel had the lowest, at 4 ppm. The average HC emission value for D70W30 fuel rose by 5.61%, whereas it dropped by 26.69% and 26.42% for D90W10 and D80W20 fuels, respectively, when compared to D100W0.

✓ D80W20 fuel had the greatest CO_2 emission value at 3 kW load, while D100W0 fuel had the lowest at 3.42% at 0.5 kW load. In comparison to D100W0 fuel, the average CO_2 emission value for D90W10, D80W20, and D70W30 fuels rose by 12.18%, 13.41%, and 12.55% respectively.

✓ While the highest NO_x value was measured as 819 ppm at 3 kW load in D80W20 fuel, the lowest NO_x value was measured as 242 ppm at 0.5 kW load in D100W0 fuel. Compared to D100W0 fuel, the average NO_x emission values increased by 6.56%, 10.56%, and 0.05% for D90W10, D80W20, and D70W30 fuels, respectively.

✓ The D90W10 fuel had the lowest BSFC value at 2 kW load, at 290.32 g/kWh, while the D70W30 fuel had the highest BSFC value at 0.5 kW load, at 800 g/kWh. Comparing D90W10, D80W20, and D70W30 fuels to D100W0 fuel, the average BSFC value increased by 7.65%, 10.02%, and 16.82%, respectively.

✓ In the tests, the D70W30 fuel had the lowest BTE value (10.42%) with a 0.5 kW load, while the D90W10 fuel had the greatest BTE value (28.70%) at a 2 kW load. In comparison to D100W0 fuel, the average BTE value dropped by 5.82%, 7.93%, and 13.61% for D90W10, D80W20, and D70W30 fuels, respectively.

✓ The RSM analysis identified CO, HC, NO_x, CO_2, BTE, and BSFC as output parameters and the waste plastic oil ratio and engine load as input factors. 97.43% for CO, 99.72% for HC, 99.76% for CO_2, 99.63% for NO_x, 97.97% for BSFC, and 97.55% for BTE were the R^2 values of the output parameters. The average errors were 5.69% for CO, 2.66% for HC, 0.99% for CO_2, 1.72% for NO_x, 4.20% for BSFC, and 4.54% for BTE.

It was found that the ideal engine load was 1.5 kW, and the ideal waste plastic oil ratio was 14%. BTE was ascertained to be 23.17%, BSFC as 371.48 g/kWh, NO_x as 495.96, CO_2 as 5.29%, HC as 21.93 ppm, and CO as 0.049% under ideal circumstances.

According to this study, the performance of engines and emission characteristics were significantly impacted by the addition of biodiesel. The inclusion of waste plastic oil resulted in notable decreases in CO and HC emissions when assessed in terms of emission metrics. This is explained by the fact that biodiesel's increased oxygen content improves combustion efficiency and results in a more thorough burning. Conversely, there were increases in emissions of NO_x and CO_2. The rise in NO_x is linked to greater combustion temperatures and oxygen content, whereas the increase in CO_2 emissions is caused by more carbon dioxide being created as a result of more efficient combustion. Based on performance metrics, it was shown that using waste plastic oil raised the BSFC value while somewhat lowering the BTE. The lower energy content of waste plastic oil in comparison to diesel fuel explains the rise in BSFC. All error rates in the RSM analyses carried out as part of the optimization studies were less than 10%, and R^2 was more than 95%, suggesting that the model converged to the results with excellent accuracy and dependability. In summary, the statistical analysis and experimental results show that waste plastic oil/diesel fuels may be safely utilized in existing diesel engines without requiring engine modifications as long as they are blended at the right ratios. This bolsters waste plastic oil's potential as an eco-friendly and sustainable alternative fuel.

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Conflict of Interest Statement

The authors declare no competing interests.

CRediT authorship contribution statement

Arif Savaş: Original draft writing, Software, Research, Methodology, Drafting, Editing, and Conceptualization.

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Nomenclature

ANN	: artificial neural networks
BSFC	: brake specific fuel consumption
BTE	: brake thermal efficiency
CO	: carbon monoxide
CO_2	: carbon dioxide
D100W0	: %100 Diesel
D100W10	: 90% Diesel + 10% Waste plas tic oil
D100W20	: 80% Diesel + 20% Waste plas tic oil
D100W30	: 70% Diesel + 30% Waste plas tic oil
HC	: hydrocarbon
MMT	: million metric tons
NO_x	: nitrogen oxide
R^2	: correlation coefficient
RSM	: response surface methodology

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