Journal of
Renewable Energy Research and Applications (RERA)

Vol. 5, No 2, 2024, 181-193 *DOI: 10.22044/rera.2023.12828.1206*

Performance Evaluation of a Thermal Barrier-coated CI Engine using Waste Oil Biodiesel Blends

Y. G. Praveen Kumar[1], B. Din[2*], R. K. Jayasimha[1], R. R. Meenakshi[1], S. Chadaram[3], K. G. Babu[4]

1. G. Pulla Reddy Engineering College (Autonomous), Kurnool, Andhra Pradesh, India.
2. Department of Mechanical and Industrial Engineering, Manipal Institute of Technology Bengaluru, Manipal Academy of Higher Education, Manipal-576104, Karnataka, India.
3. Raghu Engineering College (Autonomous), Vishakapatnam, Andhra Pradesh, India.
4. Mechanical Engineering, National Institute of Technology Andhra Pradesh, India.

Received Date 11 March 2023; Revised Date 01 July 2023; Accepted Date 03 July 2023
**Corresponding author: din.bandhu@manipal.edu (B. Din)*

Abstract

Recycling plastics into energy sources is the most promising method for cutting down on pollution and trash. In this regard, predictions of adiabatic engines using pistons with thermal barrier coatings (TBCs) were made to reduce in-cylinder heat rejection, safeguard the underlying metallic surfaces from thermal cracking, and indeed reduce engine emissions. This study compares the predicted thermal and physical parameters of plastic waste oil (WP) with its diesel blends in fixed proportions of WP10D90 (10% plastic oil, 90% diesel), WP20D80, WP30D70, WP40D60, and WP50D50 to diesel values). The study further explores the concept of the utility function to evaluate the best-ranked fuel blend in each category of various performance characteristics namely BTE, BSFC, UHC, CO, and NOx. Additionally, the effect of the thermal barrier piston coating on CI engine performance metrics and emissions was studied and compared with those achieved with regular diesel oil. When compared to diesel, the results state that the WP40D60 blend has the highest brake thermal efficiency, i.e. 31.62% at 80% load, and the lowest NOx emissions at all load conditions. In addition, it was further observed that the WP20D80 has lower hydrocarbon (HC) emissions at 20% load and an increment in CO emissions for all blends and load combinations. Overall, WP30D70 has come up with the best fuel as per the utility function.

Keywords: *Thermal barrier coating, Biodiesel blends, Brake thermal efficiency, Specific fuel consumption, Gas analyzer, Utility function.*

1. Introduction

Today, petroleum-based fuel is indispensable to the economic development of every nation. Products derived from fossil fuels continue to be the primary and most important sources of energy used to power vehicles worldwide. Nonetheless, fossil fuel reserves are limited and non-renewable [1–3]. At the current and projected crude consumption rates, it is calculable that these reserves will eventually be severely depleted, making it impossible to meet demand. In contrast, biodiesel is a renewable, clean-burning alternative fuel composed of vegetable oils or animal fats and alcohol. It contains no fossil fuel but can be emulsified with diesel in any proportion to create biodiesel. When compared to renewable energy options like solar, wind, and geothermal, biodiesel looks preferable as it is made accessible at any location and time, it doesn't require a large storage facility, and it can be produced from a diverse range of sources. Because of this, biodiesel provides a long-term and practical answer to the problem of inadequate energy supply [4–6].

Biodiesel is a sustainable alternative fuel derived from renewable resources such as vegetable oil or animal fat. Algae oil can also be utilized for its production. In the context of the compression ignition (CI) engine, it has been favored as a fuel option instead of diesel. The utilization of vegetable oil as a fuel source for compression ignition engines is not a novel concept. The inaugural compression-ignition (CI) engine, utilizing vegetable oil as fuel, was developed by Rudolf Diesel in 1895. Dr. Rudolf unveiled his invention at the 1900 World's Fair in Paris [7–9]. However, until recently, there was little enthusiasm for generating and employing vegetable oil. Biodiesel, according to ASTM D6751 standards, is a "mono-alkyl ester of long fatty acids produced from plant oil or animal fat." Standards for biodiesel were laid down in great detail by the ASTM procedure. There are procedures in place for assessing the properties of biodiesel, as well as the ranges within which such properties could be anticipated to function. Raw fossil fuel is not what biodiesel is. It is made from either vegetable oil or animal fat by the process of esterification. During the transition to esters, the characteristics of the feedstock undergo significant modifications. Biodiesel mimics the properties of its parent substance to some extent. The employed source's chemical makeup is mostly to blame for this [10–12].

Biodiesels are made from a variety of sources including discarded cooking oils, oils that are not suitable for human consumption, and those that are. Sunflower oil, mustard oil, olive oil, coconut oil, etc. are all examples of edible oils. Oils extracted from plants like jatropha and karanjia are not suitable for human consumption. A variety of cooking oils are available and utilized. Long-term heating of cooking oils causes them to undergo oxidation and create oxides and polymeric compounds. The human body cannot handle these oxides. Such oils can be recycled for other uses rather than being thrown away. The creation of biodiesel is one example of this type of use. As a food item, edible oils are both costly and in high demand, making the recycling of wasted and non-edible oils even more important. An eco-friendly fuel that burns cleanly is biodiesel. It is risk-free to use and has no negative effects on the environment. It is easily accessible and can be refreshed. The term "biodiesel" is typically used incorrectly. This phrase is frequently used to refer to either pure vegetable oil or a biodiesel and diesel mixture. Vegetable oils that have not been refined and have a high fatty acid content are not considered to be biodiesel since a conversion procedure has not been applied to them [13–16].

The biodiesel preparation methods have a significant impact on the emission values and performance of certain biodiesel-powered engines. Using a 20% blend of biodiesel tamarind seed methyl ester, Prasad *et al*. [17] examined the impact of different injection fuel methods on a CRDI engine operating under varying loads. The diesel is initially injected with 30% pilot injection (P.I) and 100% main injection (M.I) at 600 bars. Following that, TSME20 is injected at a similar pressure as the previous twin injection strategies. According to this study, the BTE for the tested biodiesel was increased by 30% PI rather than 100% MI. Furthermore, TSME20 biodiesel at 30% PI reduced hydrocarbon, carbon monoxide, and smoke emissions significantly when compared to 100% diesel MI at high load conditions. Reddy et al. [18] studied the behavior of a diesel engine powered by biodiesel blends containing corn seed methyl esters (CSME). According to the results of the tests, the CSME B20 (20% biodiesel and 80% diesel) operated engine had higher BTE when compared to other blends, implying that CSME B20 is a viable fuel among the alternative diesel options. Kumari *et al*. [19] used peeled lemon oil as a novel fuel to power a CI engine under varying load conditions. Based on the results of the experiments, it was discovered that B20 had better BTE, BSFC, and engine emissions of CO, smoke, and HC when compared to other blends. Ahmed *et al*. [20] examined the performance, combustion, and emission analysis of many biodiesel blends made from animal fat methyl ester (AF), waste cooking oil (WCO), and petro-diesel (PD). According to the results of the tests, PD50AF30WCO20 consumes less BSFC and more BTE than the other tested blends. Emissions in the AF50WCO50 blend were found to be 28% higher in CO and 22% lower in UHC, resulting in the greatest portion of heat rejection rate with a lower amount of CO, NOx, and smoke when compared to other blends. Prabakaran and Viswanathan [21] tested the performance, combustion, and emission characteristics of cotton seed oil methyl ester blends and anhydrous ethanol in a diesel engine at many loads. The results show that the BTE of the blends is closer to diesel. Emissions of NOx, smoke, CO, and HC decrease at maximum loads and improve at lower loads. Srithar *et al*. [22] investigated the usage of a thermal barrier-coated combustion chamber on the performance of a dual biodiesel DPN-powered diesel engine (diesel, Pongamia, neem). According to the observations, the SFC of a coated engine (CE) with DPN 1 fuel (a mixture of 75% diesel, 22.5% Pongamia oil, and 2.5%) is 13.9% lower than that of a base engine. The DPN 1 CE engine has a BSFC that is 12% higher than the diesel engine. CE emits less HC and produces less smoke than the baseline engine. Dewangan *et al*. [23] compared the emission values and performance of a multi-cylinder engine powered by Karanja methyl ester (KME), Manilkara zapota methyl ester (MZME), and diesel. Biodiesel of 20% each, denoted by MZME20 and KME20, was tested in the engine to determine its performance at various engine speeds. The experimental results revealed that both biodiesel blends had higher BSFC and lower BP than neat diesel operation. HC and CO emissions at full load were lower, while NOx emissions for blended fuel were higher compared to diesel fuel.

The prior state of the arts described the significance of thermal barrier coatings (TBCs) in enhancing engine performance. TBCs play an important role in reducing in-cylinder heat rejection in CI engines. TBCs are applied to the surfaces of pistons and other engine components that are exposed to high temperatures. These coatings act as insulation, reducing the amount of heat that is transferred to the underlying metal surfaces. This helps to prevent thermal cracking and other forms of damage that can occur when metal components are exposed to high temperatures. In addition to protecting the underlying metal surfaces, TBCs also improve engine performance by reducing heat loss from the combustion chamber. This can increase the thermal efficiency of the engine, resulting in better fuel economy and lower emissions. TBCs can also reduce the formation of nitrogen oxides (NOx), which are a major contributor to air pollution. Thus TBCs not only protect the engine components from high temperatures and reduce emissions but also their application reduces the environmental impact and improves overall engine performance [24–26].

In this context, an attempt has been made by the authors to evaluate the performance and emissions characteristics of a thermal barrier-coated CI engine. The novel aspect of this work is the use of plastic waste oil (PWO) as a feedstock for biodiesel production, as well as the effects of using plastic waste oil on performance parameters such as thermal efficiency, fuel consumption, and emissions such as HC, CO, and NOx for thermal barrier-coated CI engines. Using plastic waste oil to produce biodiesel is a novel way to address two environmental problems: pollution caused by fossil fuels and the accumulation of non-biodegradable plastic waste. This approach aims to enhance engine performance by coating engine parts with thermal barrier coatings, reducing pollution and trash by recycling plastic into energy sources, and using alternative fuels.

2. Materials and method

Petroleum waste contributes to the large volume of plastic waste generated both in the household and the industrial sectors, which requires hundreds of years to decompose. In general, the waste management method that is most popular is landfill management, and plastic is the most commonly recycled material. The landfill method is currently popular for waste management, but it needs a more landfill area and has an effect on the environment, resulting in soil contamination. Moreover, it can provide environmental benefits in terms of waste management for maximum benefits and reduction in plastic waste, reduction in plastic waste disposal, and minimizing landfill space issues. Waste plastic contains HCs, which are the primary element of traditional fuels. This increases the probability of reusing these waste plastics by converting them into fuel. Products can be acquired from the production process as well as used as an energy source like conventional fuels [27, 28]. It can also supply environmental comforts in terms of waste management for extreme comforts and depletion in the amount of waste plastic, as well as reduced waste plastic destruction and limiting the difficulty of finding areas for scraping landfills. The use of waste plastic as a renewable energy source material also contributes to the reduction of the energy emergency [29]. Much research supports the use of biodiesel as an alternative to diesel fuel, and it is anticipated that the energy transportation sector will use it as a renewable energy source. Oxygen in fuel molecules is expected to result in cleaner biodiesel combustion, leading to improvements when considering emission. Various studies have been conducted to investigate the use of plastic waste oil as a replacement fuel in CI engines. Plastic waste pyrolysis oil has properties close to diesel fuel, such as density, cetane index, and heating value can be used as a diesel fuel alternative. This waste plastic oil is processed via transesterification and then blended with diesel [30, 31]. The experiment was accomplished in a single-cylinder CI engine, and the fractions of the blend used for the analysis were 10%, 20%, 30%, 40%, and 50% of WP contents added on in neat biodiesel by volume basis.

Table 1. Fuel properties.

S. No	Fuel	Density	Caloric value	Kinematic viscosity	Flash point	Fire point
		@ 15 ^{0}C (kg/m^3)	(MJ/kg)	@40 ^{0}C (mm^2/s)	(^{0}C)	(^{0}C)
1	Diesel	835	44	2.7	55	66
2	WP10D90	809.5	43.24	3.2	47	57.6
3	WP20D80	808.8	42.82	3.65	45	59.6
4	WP30D70	808.4	42.4	3.9	47.6	62
5	WP40D60	807.8	41.63	4.3	55	64
6	WP50D50	807.5	41.02	4.6	46.3	58

2.1. Test engine setup

The experiments were carried out on a Kirloskar single-cylinder, water-cooled, compression ignition test engine linked with a swing field dynamometer as shown in figure 1. The machine specifications are listed in table 2. The AVL 5 gas analyzer is used to enumerate the engine tailpipe discharge, which measures emissions such as HC, CO_2, CO, NO_X, and O_2. Similarly, an AVL smoke meter is used to calculate the smoke concentration in the exhaust, and figure 1 depicts the schematic view of the experimental setup.

Figure 1. Test engine setup used for experimentation.

Table 2. Engine specifications.

Property	Description
Name	Kirloskar engine
Type	4 stroke, 1 cylinder, DI, water-cooled, CI Engine
Bore	80 mm
Stroke	110 mm
Speed	1500 rpm
B.H.P.	5 kW
Compression ratio	16:1
Diameter of the brake drum	360 mm
The thickness of the belt	5 mm
Co-efficient of discharge	0.6
Diameter of the orifice	20 mm
Maximum current	13 amp

The trials were carried out on the engine using diesel with normal plain piston, and the tests were later repeated with the WP10D90, WP20D80, WP30D70, WP40D60, and WP50D50 blends with anodizing coated piston (Figure 2) at load variations and rated speeds. The experimental observations were recorded, and several performance parameters and emission characteristics were noted and compared at standard operating conditions between base diesel fuel and various blends.

(a) Before anodizing coating **(b) After anodizing coating**

Figure 2. Piston top view before and after anodizing coating.

2.2. Utility function

Utility functions are a commonly accepted concept in multi-criteria decision-making (MCDM) problems due to their simplicity and ease of understanding for decision-makers. They do not require any additional constraints beyond the aggregation formula. In the utility-based Taguchi process, an MCDM problem can be transformed into a single response optimization problem using a response function, also known as an arbitrary function, which acts as an overall utility index. The goal is to optimize this function to obtain the solution [32–34]. According to the utility function approach [35], if A_x is the performance indicator of an output response x and there are k output characteristics evaluating the data set, the joint utility function can be expressed as follows:

$$\mathbf{U(A_1, A_2, \ldots\ldots\ldots A_k) = f\{U_1(A_1), U_2(A_2), \ldots\ldots\ldots U_k(A_k)\}} \quad (1)$$

In equation (1), the utility of the x_{th} output response is represented by $(U_1(A_1))$. Equation (2) shows the overall utility function, which is equal to the sum of the utilities of individual output characteristics.

$$\mathbf{U(A_1, A_2, \ldots\ldots\ldots A_k) = \sum_{x=1}^{k} U_x(A_x)} \quad (2)$$

The weightage given to the output responses is based on their relative importance and impact on the process. In this case, the overall utility function can be understood as follows:

$$\mathbf{U(A_1, A_2, \ldots\ldots\ldots A_k) = \sum_{x=1}^{k} W_x U_x(A_x)} \quad (3)$$

In equation (3), W_x represents the importance or influence assigned to the output response x. The total of all the weights assigned to all the output responses should be 1. The output values are evaluated based on lower and higher values using two random arithmetic values 0 and 9 (preference numbers) as benchmarks. Equation (4) can be used to evaluate the preference number N_p on a logarithmic scale.

$$\mathbf{N_p = O * \log \frac{A_x}{A'_x}} \quad (4)$$

In equation (4), A_x represents the value of output characteristic x. A'_x is the lower value of output characteristic x. O is a constant and can be calculated using equation (5), only if $A_x = A^*$ (where A^* is the optimal value), then $N_p = 9$.

The value of output response x is represented by A_x in equation (4). The lower value of output response x is represented by A'_x. O is a constant that can be found using equation (5) if A_x is equal to the optimal value, denoted as A^*. If this is the case, then N_p is equal to 9. Therefore,

$$\mathbf{O = \frac{9}{\log \frac{A_x}{A'_x}}} \quad (5)$$

The utility in its whole is expressed as:

$$\mathbf{U = \sum_{x=1}^{k} W_x(N_p)} \quad (6)$$

Under the condition:

$$\mathbf{\sum_{x=1}^{k} W_x = 1} \quad (7)$$

The S/N ratio concept developed by Taguchi involves three different output characteristics: nominal-is-best (NB), lower-is-better (LB), and higher-is-better (HB). Among these, HB is relevant for evaluating utility functions.

Therefore, when maximizing the utility function, the output attributes considered in the assessment process will be automatically optimized, either by being minimized or maximized, depending on the specific situation.

3. Results and discussion

3.1. BTE variations with load

The effectiveness of the IC engine in converting and utilizing the chemical energy of fuel in the form of mechanical energy is signified by BTE. When using fuel blends in an IC engine, the BTE may vary depending on the load. The BTE tends to be higher at higher loads as more of the energy in the fuel is being converted into useful work. However, the BTE may be lower at low loads as more of the energy in the fuel is being lost as heat [36, 37]. The experimental values are displayed in table 3. Utility function was applied and the fuel WP40D60 corresponding to the highest value of 25.69 was assigned first rank for maximum BTE (Table 3). A graphical representation of the experimental data has been shown in figure 3. It depicts the BTE variations of a coated piston with plastic waste oil and diesel fuel under various load conditions.

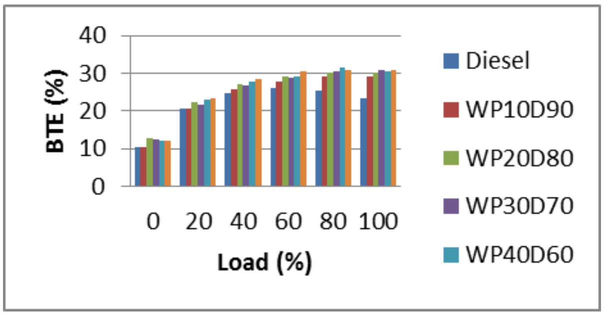

Figure 3. BTE variations with load.

The BTE of the engine increases as the load increases; additionally, the combined calorific value and density of the fluid flow play a major role in attaining BTE. At a maximum load of 60%, the BTE was 26.08% for diesel with a plain piston and 31.62% for a WP40D60 blend with a coated piston. As a result, when compared to other blends, WP biodiesel achieved a higher combustion BTE and good thermal performance in the WP40D60 combination. These outputs are very close to a couple of findings discussed by researchers [38–40].

Table 3. Experimental values of BTE with load variation and overall utility.

Fuel	U_1	U_2	U_3	U_4	U_5	U_6	$U_{overall}$	Rank
Diesel	10.5	20.7	24.6	26.08	25.57	23.44	21.82	6
WP10D90	10.31	20.56	25.68	27.64	29.31	29	23.75	5
WP20D80	12.79	22.27	27.02	28.99	30.32	30.29	25.28	3
WP30D70	12.47	21.7	26.82	28.95	30.41	30.75	25.18	4
WP40D60	12.03	22.87	27.86	29.2	31.62	30.56	25.69	1
WP50D50	12.27	23.28	28.22	30.05	30.16	30.11	25.68	2

3.2. BSFC variations with load

BSFC is a measure of how much fuel an engine consumes per unit of power output. It is typically measured in grams of fuel per kilowatt-hour (g/kWh) or pounds of fuel per horsepower-hour (lb/hph). BSFC is inversely proportional to the thermal efficiency of the engine, meaning that the lower the BSFC, the higher the thermal efficiency. When using biodiesel blends in an IC engine, the BSFC can be affected by several factors, including the type of fuel used, the engine design, and the operating conditions. The BSFC may vary depending on the load. It is typically lower at higher loads as more of the energy in the fuel is being converted into useful work and less is lost as heat. However, the BSFC may be higher at low loads as more of the energy in the fuel is being lost as heat [41–44]. The experimental values are displayed in table 4. Utility function was applied and the fuel WP40D60 corresponding to the lowest value of 0.348 was assigned first rank for minimum BSFC (Table 4). A graphical representation of the experimental data has been shown in figure 4.

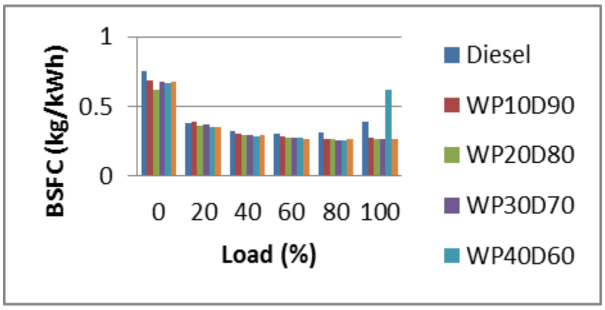

Figure 4. BSFC variations with load.

It depicts the BSFC variations of a coated piston with plastic waste oil and diesel fuel under various load conditions.

At any load condition, the better fuel had a lower BSFC value. The BSFC of diesel and WP fuel decreased as the engine load increased at all loads. When loaded to 80%, WP30D70 has the lowest BSFC value of all biodiesel blends. This is due to the increased stability of the energy content and combustion process which is further characterized by Afsal et al. [45], Pandhare and Padalkar [46], and Chiatti et al. [47] in their studies.

3.3. HC emission variations with load

Hydrocarbon (HC) emissions are a type of air pollutant. They are composed of molecules made up of hydrogen and carbon atoms and are created when the fuel is not completely combusted in the engine. These emissions are harmful to human health and the environment and are one of the pollutants regulated by the Environmental Protection Agency (EPA) [48, 49]. The experimental values are displayed in table 5. Utility function was applied and the fuel WP20D80 corresponding to the lowest value of 69.00 was assigned first rank for minimum HC emissions (Table 5). A graphical representation of the experimental data has been shown in figure 5.

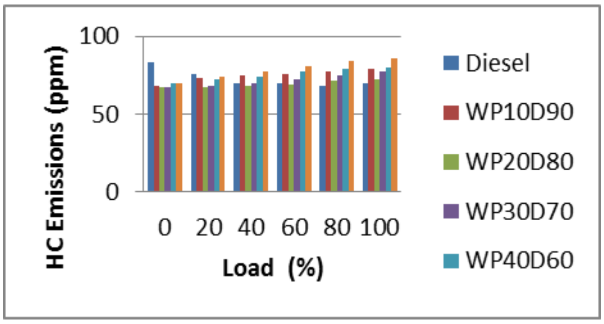

Figure 5. HC Emissions variations with load.

It depicts the HC emissions variations of a coated piston with plastic waste oil and diesel fuel under various load conditions. Unburned emissions of HC are released into the environment during the combustion of a heterogeneous air and fuel mixture in a compression ignition engine. The HCs in many blends have been increasing, and it has been discovered that WP20D80 has lower HC emissions at 20% load. As reported in previous works of literature [50–53], high in-cylinder temperatures and brisk combining of the fuel and air mixture promote absolute combustion of the fuel, lowering emissions of HC.

Table 4. Experimental values of BSFC with load variation and overall utility.

Fuel	U_1	U_2	U_3	U_4	U_5	U_6	$U_{overall}$	Rank
Diesel	0.75	0.38	0.32	0.304	0.31	0.338	0.400	6
WP10D90	0.769	0.386	0.309	0.287	0.271	0.273	0.383	5
WP20D80	0.639	0.357	0.294	0.274	0.267	0.264	0.349	2
WP30D70	0.655	0.353	0.279	0.277	0.259	0.263	0.348	1
WP40D60	0.668	0.35	0.288	0.277	0.256	0.262	0.350	3
WP50D50	0.674	0.355	0.291	0.27	0.268	0.269	0.355	4

Table 5. Experimental values of HC emissions with load variation and overall utility.

Fuel	U_1	U_2	U_3	U_4	U_5	U_6	$U_{overall}$	Rank
Diesel	83	76	70	70	68	70	72.83	3
WP10D90	68	73	75	76	77	79	74.67	4
WP20D80	67	67	68	69	71	72	69.00	1
WP30D70	67	68	70	72	75	77	71.50	2
WP40D60	70	72	74	77	79	80	75.33	5
WP50D50	72	74	77	81	84	86	79.00	6

3.4. CO emission variations with load

Similar to HC emissions, CO emissions are also a type of air pollutant regulated by the Environmental Protection Agency (EPA). The effect of fuel blends on CO emissions can vary depending on the type of fuel used, the engine design, and the operating conditions. In general, biodiesel blends have been shown to reduce CO emissions when compared to petroleum diesel. This is because biodiesel contains fewer carbon and hydrogen atoms than diesel, which means that less CO is produced when biodiesel is combusted. Biodiesel's high viscosity creates atomization of fuel particles, and the formation of a regular fuel-to-air ratio is tricky, which results in CO emissions during combustion [54–56]. The experimental values are displayed in table 6. Utility function was applied and it was observed that the diesel emits the lowest CO as compared to the other fuel blends (Table 6).

Table 6. Experimental values of CO emissions with load variation and overall utility.

Fuel	U_1	U_2	U_3	U_4	U_5	U_6	$U_{overall}$	Rank
Diesel	0.07	0.06	0.06	0.06	0.06	0.11	0.070	1
WP10D90	0.09	0.08	0.07	0.07	0.06	0.06	0.072	2
WP20D80	0.09	0.09	0.08	0.08	0.07	0.11	0.087	2
WP30D70	0.11	0.1	0.09	0.09	0.09	0.08	0.093	4
WP40D60	0.12	0.11	0.1	0.1	0.09	0.09	0.102	5
WP50D50	0.14	0.13	0.12	0.12	0.12	0.11	0.123	6

A graphical representation of the experimental data has been shown in figure 6.

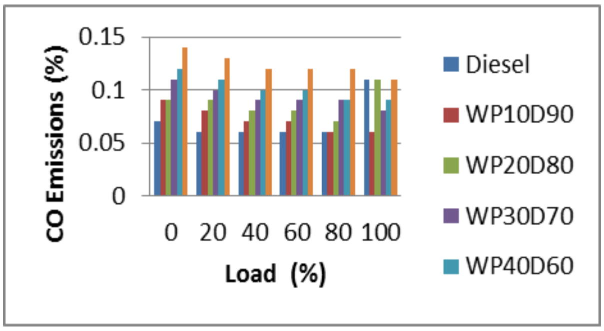

Figure 6. CO Emissions variations with load.

It depicts the CO emissions variations of a coated piston with plastic waste oil and diesel fuel under various load conditions. The graph clearly shows that CO emissions increase in all blend and load combinations when compared to diesel.

3.5. NO$_X$ emission variations with load

Engineers and makers of diesel engines typically plan for strict control of NOx emissions. Fuel NOx is produced when nitrogen in the fuel reacts with oxygen in the presence of combustion air to produce nitrogen oxides. Gaseous fuels seldom have this issue. However, fuel NOx can make up as much as half of the overall NOx emissions in oils with high levels of fuel-bound nitrogen. Occasionally, prompt NOx production takes place when ambient nitrogen reacts quickly with hydrocarbon molecules. In most cases, the amount of NOx produced immediately after combustion is rather little. As NOx emissions are lowered significantly, nevertheless, this source becomes increasingly significant [57–59]. In compression ignition engines, the amount of oxygen in the air, the temperature of the flame, and the amount of time since ignition are the key determinants of the increase in NOx emissions. Additionally, NOx levels are increased by a longer residence duration at higher temperatures [60, 61]. This research work, however, found that NOx emissions are lower than those of diesel in all load conditions except full load. Testing shows that reducing the amount of diesel in a mix and increasing the amount of biodiesel results in lower NOx emissions. Several researchers conducted tests of biodiesel blends in internal combustion engines and came up with findings that were comparable to one another [62–65]. The experimental values are displayed in table 7. Utility function was applied and it was observed that all the fuel blends significantly emit less NOx as compared to diesel as shown in table 7. The result further recognizes WP20D80 as the best fuel blend for low NOx emissions. A graphical representation of the experimental data has been shown in figure 7 which shows that the NOx emissions are steadily reduced with all combinations except at full load.

Table 7. Experimental values of NOx emissions with load variation and overall utility.

Fuel	U_1	U_2	U_3	U_4	U_5	U_6	$U_{overall}$	Rank
Diesel	133	297	558	720	764	801	546	6
WP10D90	137	267	460	626	685	844	503	5
WP20D80	110	232	385	492	610	757	431	1
WP30D70	94	275	441	537	749	819	486	3
WP40D60	93	225	423	639	743	885	501	4
WP50D50	84	195	272	548	710	917	454	2

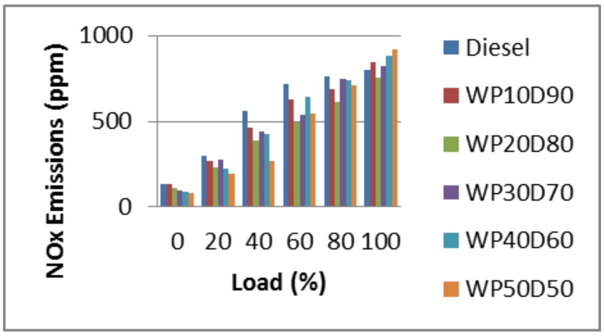

Figure 7. NOx emission variations with load.

3.6. Selection of best fuel

The implementation of the utility function was done for choosing the best fuel. In this regard, a decision matrix was formed by the accumulation of all the performance characteristics, as shown in table 8.

Table 8. Formation of a decision matrix.

Fuel	BTE	BSFC	HC	CO	NOx
Diesel	28.09	0.400	72.83	0.070	546
WP10D90	32.40	0.383	74.67	0.072	503
WP20D80	25.28	0.349	69.00	0.087	431
WP30D70	34.77	0.348	71.50	0.093	486
WP40D60	32.26	0.350	75.33	0.102	501
WP50D50	33.35	0.355	79.00	0.123	454

These values were brought on the same scale using equations 4 and 5. All these performance characteristics have been treated equally. Using, equations 2 and 3, the individual utility functions were calculated as shown in table 9. Overall, all utility was calculated using equation 6, and the ranks were assigned as shown in table 10.

Table 9. Normalization and calculation of individual utility.

Fuel	U_1	U_2	U_3	U_4	U_5
Diesel	2.97	0.05	5.40	8.96	0.03
WP10D90	7.01	2.85	3.75	8.58	3.12
WP20D80	0.00	8.67	9.00	5.56	9.04
WP30D70	9.00	8.95	6.63	4.39	4.46
WP40D60	6.88	8.49	3.16	3.03	3.26
WP50D50	7.82	7.71	0.00	0.04	7.02

Table 10. Overall utility and ranking.

Fuel	$U_{overall}$	Rank
Diesel	3.46	6
WP10D90	5.06	3
WP20D80	6.45	2
WP30D70	**6.69**	**1**
WP40D60	4.96	4
WP50D50	4.50	5

4. Conclusions and Future Scope

The current study looked into the feasibility of employing plastic waste oil instead of diesel fuel in the operation of a CI engine. The properties of WPO have been tested at various proportions, such as WP10D90, WP20D80, WP30D70, WP40D60, and WP50D50. The performances of WP and diesel were compared at these various diesel/waste plastic oil blend proportions. Utility function was also applied for the best fuel selection. In addition, the effects of piston coatings in engines on emissions are compared to diesel. When comparing the results of all biodiesel blends, the following conclusions were drawn:

- WP40D60 has a high BTE of 31.62 percent at 80% load and the lowest BSFC value of all biodiesel blends at 80% load.
- When compared to diesel, the WP40D60 emission model possesses the lowest level of NOx fumes under no-load conditions, whereas the WP20D80 yields lower HC-derived emissions at 20% load. In all other blends and loading arrangements, CO emissions increase overall.
- The ranking of the best fuel for each performance characteristic using the Utility function is WP40D60 for BTE, WP30D70 for BSFC, WP20D80 for HC emissions, diesel for CO emissions, and WP20D80 for NOx emission.
- Based on the overall performance characteristics, the utility function approach recommends WP30D70 as the best fuel for a thermal barrier-coated CI Engine.
- Lastly, thermal barrier coatings are put on engine parts like pistons, valves, and chambers to simulate adiabatic engines. This lowers the amount of heat that is lost from the cylinder, protects the metal parts underneath from thermal fatigue, and reduces the amount of pollution the engine puts out.

The work may be further extended for performance evaluation and optimization of various process parameters in line with sustainable environmental conditions. The possible future extensions of the work are discussed as follows:

- For the same engine, the timing and pressure of the injections can be changed to get better combustion and less pollution.
- Installing after-treatment devices in the engine's exhaust can lower emissions.
- The engine's performance and emissions can be improved by incorporating nano additives and alcohols into the biodiesel.

5. References

[1] Demirbas, A. and Karslioglu, S. (2007). Biodiesel production facilities from vegetable oils and animal fats. Energy Sources, Part A: Recovery, Utilization and Environmental Effects, Vol. 29, No. 2, pp 133–141. https://doi.org/10.1080/009083190951320

[2] Ghazvini, M., Pourkiaei, S., and Pourfayaz, F. (2020). Thermo-Economic Assessment and Optimization of Actual Heat Engine Performance by Implemention of NSGA II. Renewable Energy Research and Applications, 1(2), 235-245. doi: https://doi.org/10.22044/rera.2020.9677.1034

[3] Warkhade, G. S., Katam, G. B., and Alur, V. B. (2023). Experimental Analysis and Parametric Optimization of Linseed Oil Methyl Ester Blends Fueled Variable Compression Ratio Diesel Engine. Renewable Energy Research and Applications. doi: https://doi.org/10.22044/rera.2022.12394.1177

[4] Damanik, N., Ong, H. C., Chong, W. T., and Silitonga, A. S. (2017). Biodiesel production from Calophyllum inophyllum−palm mixed oil. Energy Sources, Part A: Recovery, Utilization and Environmental Effects, Vol. 39, No. 12, pp 1283–1289. https://doi.org/10.1080/15567036.2017.1324537

[5] Muvvala, P. and Bandhu, D. (2023). The influence of flow blockage elements at the orifice exit on the hydrodynamic and thermal performances of impinging square jets - an experimental investigation. Heat Mass Transfer. https://doi.org/10.1007/s00231-023-03371-x

[6] Demisu, D., Kebede, S., and Wondifraw, D. (2023). Hybridization of Moringa stenopetala and Azadirachta indica Seed Oil to Synthesize Biodiesel with Improved Quality. Renewable Energy Research and Applications, 4(1), 1-12. doi: https://doi.org/10.22044/rera.2022.11955.1127

[7] Khan, M. Y., Rao, P. S., Pabla, B. S., & Ghotekar, S. (2022). Innovative biodiesel production plant: Design, development, and framework for the usage of biodiesel as a sustainable EDM fluid. Journal of King Saud University - Science, Vol. 34, No. 6, pp 102203. https://doi.org/10.1016/j.jksus.2022.102203

[8] Solangi, F. A., Memon, L. A., Samo, S. R., Luhur, M. R., Bhutto, A. A., and Ansari, A. M. (2022). Investigation of Performance and Emission Characteristics of CI Engine Using Diesel and Waste Cooking Oil Blends. Energies, Vol. 15, No. 19, pp 7211. https://doi.org/10.3390/en15197211

[9] Adin, M. S., Altun, S., and Adin, M. S. (2022) Effect of using bioethanol as fuel on start-up and warm-up exhaust emissions from a diesel power generator, International Journal of Ambient Energy, 43:1, 5711-5717,

DOI: https://doi.org/10.1080/01430750.2021.1977387

[10] Moreno-Garcia, L., Gariépy, Y., Barnabé, S., and Raghavan, V. (2021). Factors affecting the fatty acid profile of wastewater-grown-algae oil as feedstock for biodiesel. Fuel, Vol. 304, pp 121367. https://doi.org/10.1016/J.FUEL.2021.121367

[11] Etim, A. O., Jisieike, C. F., Ibrahim, T. H., and Betiku, E. (2022). Biodiesel and its properties. Production of Biodiesel from Non-Edible Sources: Technological Updates, pp 39–79. https://doi.org/10.1016/B978-0-12-824295-7.00004-8

[12] Altun Ş, Adin MŞ, İlçin K. (2023) Monohydric aliphatic alcohols as liquid fuels for using in internal combustion engines: A review. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering. doi: https://doi.org/10.1177/09544089231160472

[13] Ranjan, A., Dawn, S. S., Nirmala, N., Santhosh, A., and Arun, J. (2022). Application of deep eutectic solvent in biodiesel reaction: RSM optimization, CI engine test, cost analysis and research dynamics. Fuel, Vol. 307, pp 121933. https://doi.org/10.1016/J.FUEL.2021.121933

[14] Altun, S., Öner, C., Yaşar, F., Adin, Hamit. (2011). Effect of n-Butanol Blending with a Blend of Diesel and Biodiesel on Performance and Exhaust Emissions of a Diesel Engine Industrial & Engineering Chemistry Research 2011 50 (15), 9425-9430 DOI: https://doi.org/10.1021/ie201023f

[15] Rajesh, R., Vijaya Bhaskar Reddy, C., and Durga Prasad, B. (2023). Mechanical modeling and design of YSZ ceramic coated piston for effective performance in an IC Engine. International Journal on Interactive Design and Manufacturing, pp 1–7. https://doi.org/10.1007/S12008-022-01187-3/FIGURES/6

[16] Van Gerpen, J. H. and He, B. B. (2014). Biodiesel and renewable diesel production methods. Advances in Biorefineries: Biomass and Waste Supply Chain Exploitation, pp 441–475. https://doi.org/10.1533/9780857097385.2.441

[17] Bala Prasad, K., Meduri, O., Dhana Raju, V., Azmeera, A. K., Venu, H., Subramani, L., and Soudagar, M. E. M. (2020). Effect of split fuel injection strategies on the diverse characteristics of CRDI diesel engine operated with tamarind biodiesel. Energy Sources, Part A: Recovery, Utilization and Environmental Effects. https://doi.org/10.1080/15567036.2020.1856973

[18] Rama Krishna Reddy, E., Subbalakshmi, Y., Dhana Raju, V., Appa Rao, K., Harun Kumar, M., Rami Reddy, S., and Tharun Sai, P. (2022). Assessment of performance, combustion and emission characteristics of the diesel engine powered with corn biodiesel blends. International Journal of Ambient Energy, Vol. 43, No. 1, pp 435–443. https://doi.org/10.1080/01430750.2019.1636867

[19] Aruna Kumari, A., Sivaji, G., Arifa, S., Sai Mahesh, O., Raja Rao, T., Venkata Kalyan, S., and Lakshman Reddy, K. (2020). Experimental assessment of performance, combustion and emission characteristics of diesel engine fuelled with lemon peel oil. https://doi.org/10.1080/01430750.2020.1861089, Vol. 43, No. 1, pp 3857–3867. https://doi.org/10.1080/01430750.2020.1861089

[20] Ahmed, S. A., Rahamathullah, I., and Jafer, K. S. (2021). Investigation of petro-diesel, waste animal fat biodiesel with waste cooked oil biodiesel different blends in single cylinder four-stroke water-cooled CI engine. Energy Sources, Part A: Recovery, Utilization and Environmental Effects, Vol. 43, No. 12, pp 1413–1428. https://doi.org/10.1080/15567036.2019.1655113

[21] Prabakaran, B. and Viswanathan, D. (2018). Experimental investigation of effects of addition of ethanol to bio-diesel on performance, combustion and emission characteristics in CI engine. Alexandria Engineering Journal, Vol. 57, No. 1, pp 383–389. https://doi.org/10.1016/J.AEJ.2016.09.009

[22] Srithar, K., Arun Balasubramanian, K., Vivar, M., and Skryabin, I. (2013). An Experimental Investigation on Diesel and Low Heat Rejection Engines with Dual Biodiesel Blends. http://dx.doi.org/10.1080/15435075.2012.738448, Vol. 10, No. 10, pp 1041–1055. https://doi.org/10.1080/15435075.2012.738448

[23] Dewangan, A., Yadav, A. K., Mallick, A., Pal, A., and Singh, S. (2019). Comparative study of Manilkara zapota and Karanja based biodiesel properties and its effect on diesel engine characteristics., Vol. 44, No. 2, pp 5143–5153. https://doi.org/10.1080/15567036.2019.1661551

[24] Mehta, A., Vasudev, H., and Singh, S. (2021). Performance Status of Different Advanced Thermal Barrier Coatings against Failure Mechanisms in Gas Turbines. Thermal Spray Coatings, pp 189–208. https://doi.org/10.1201/9781003213185-7

[25] Mehta, A., Vasudev, H., and Singh, S. (2020). Recent developments in the designing of deposition of thermal barrier coatings – A review. Materials Today: Proceedings, Vol. 26, pp 1336–1342. https://doi.org/10.1016/J.MATPR.2020.02.271

[26] Bhardwaj, A.R., Vaidya, A.M., Meshram, P.D., and Bandhu, D. (2023). Machining behavior investigation of aluminium metal matrix composite reinforced with TiC particulates. Int J Interact Des Manuf. https://doi.org/10.1007/s12008-023-01378-6

[27] Mangesh, V. L., Padmanabhan, S., Tamizhdurai, P., and Ramesh, A. (2020). Experimental investigation to identify the type of waste plastic pyrolysis oil suitable for conversion to diesel engine fuel. Journal of Cleaner Production, Vol. 246, pp 119066.

https://doi.org/10.1016/J.JCLEPRO.2019.119066

[28] Yadav, G. P. K., Bandhu, D., Krishna, B. V., Gupta, N., Jha P., Vora J. J., Mishra, S., Saxena, K. K., Salem, K. H., and Abdullaev, S. S. (2023) Exploring the potential of metal-cored filler wire in gas metal arc welding for ASME SA387-Gr.11-Cl.2 steel joints, Journal of Adhesion Science and Technology, DOI: https://doi.org/10.1080/01694243.2023.2223367

[29] Oni, B. A., Sanni, S. E., and Olabode, O. S. (2021). Production of fuel-blends from waste tyre and plastic by catalytic and integrated pyrolysis for use in compression ignition (CI) engines. Fuel, vol. 297, pp 120801. https://doi.org/10.1016/j.fuel.2021.120801

[30] Mariappan, M., Panithasan, M. S., and Venkadesan, G. (2021). Pyrolysis plastic oil production and optimisation followed by maximum possible replacement of diesel with bio-oil/methanol blends in a CRDI engine. Journal of Cleaner Production, Vol. 312, pp 127687. https://doi.org/10.1016/J.JCLEPRO.2021.127687

[31] Dinbandhu, Abhishek, K. (2021). Parametric Optimization and Evaluation of RMD^{TM} Welding Performance for ASTM A387 Grade 11 Steel Plates Using TOPSIS-Taguchi Approach. In: Patnaik, A., Kozeschnik, E., Kukshal, V. (Eds.) Advances in Materials Processing and Manufacturing Applications. iCADMA 2020. Lecture Notes in Mechanical Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-16-0909-1_22

[32] Vinay, D. L., Keshavamurthy, R., Erannagari, S., Gajakosh, A., Dwivedi, Y. D., Bandhu, D., Tamam, N., and Saxena, K. K. (2023) Parametric analysis of processing variables for enhanced adhesion in metal-polymer composites fabricated by fused deposition modeling, Journal of Adhesion Science and Technology, DOI: https://doi.org/10.1080/01694243.2023.2228496

[33] Kumari, S., Bandhu, D., Kumar, A., Yadav, R. K., and Vivekananda, K. (2020). Application of Utility Function Approach Aggregated with Imperialist Competitive Algorithm for Optimization of Turning Parameters of AISI D2 Steel. In Recent Advances in Mechanical Infrastructure (pp. 49–57). Springer, Singapore. https://doi.org/10.1007/978-981-32-9971-9_6

[34] Murali Mohan, M., Venugopal Goud, E., Deva Kumar, M. L. S., Kumar, V., Kumar, M., and Dinbandhu. (2021). Parametric Optimization and Evaluation of Machining Performance for Aluminium-Based Hybrid Composite Using Utility-Taguchi Approach. In Lecture Notes in Mechanical Engineering (pp. 289–300). Springer, Singapore. https://doi.org/10.1007/978-981-16-3033-0_27

[35] Deb Barma, J., Roy, J., Saha, S. C., and Roy, B. S. (2012). Process parametric optimization of submerged arc welding by using utility based Taguchi concept. Advanced Materials Research, vol. 488–489, pp 1194–1198. https://doi.org/10.4028/www.scientific.net/AMR.488-489.1194

[36] Altarazi, Y. S. M., Abu Talib, A. R., Yusaf, T., Yu, J., Gires, E., Ghafir, M. F. A., and Lucas, J. (2022). A review of engine performance and emissions using single and dual biodiesel fuels: Research paths, challenges, motivations and recommendations. Fuel, Vol. 326, pp 125072. https://doi.org/10.1016/J.FUEL.2022.125072

[37] Kaisan, M. U., Anafi, F. O., Nuszkowski, J., Kulla, D. M., and Umaru, S. (2020). Calorific value, flash point and cetane number of biodiesel from cotton, jatropha and neem binary and multi-blends with diesel. Biofuels, Vol. 11, No. 3, pp 321–327. https://doi.org/10.1080/17597269.2017.1358944

[38] Das, A. K., Hansdah, D., Mohapatra, A. K., and Panda, A. K. (2020). Energy, exergy and emission analysis on a DI single cylinder diesel engine using pyrolytic waste plastic oil diesel blend. Journal of the Energy Institute, Vol. 93, No. 4, pp 1624–1633. https://doi.org/10.1016/J.JOEI.2020.01.024

[39] Praveen Kumar Yadav, G., Shaikshavali, G., and Lava Kumar, M. (2019). Experimental investigation on the performance of ci engine using waste plastic pyrolysis oil (WPPO) with thermal barrier coating on piston and thermal analysis of the piston using ansys. International Journal of Mechanical and Production Engineering Research and Development, Vol. 9, No. 3, pp 1323–1334. https://doi.org/10.24247/ijmperdjun2019138

[40] Dhana Raju, V., Kishore, P. S., and Yamini, K. (2018). Experimental Studies on Four Stroke Diesel Engine Fuelled with Tamarind Seed Oil as Potential Alternate Fuel for Sustainable Green Environment. European Journal of Sustainable Development Research, Vol. 2, No. 1, pp 10. https://doi.org/10.20897/ejosdr/78489

[41] Emara, A. K. and Ghazaly, N. M. (2022). A Review on the Performance Analysis of C.I Engine with Biofuel Blends. SVU-International Journal of Engineering Sciences and Applications, Vol. 3, No. 2, pp 27–36. https://doi.org/10.21608/svusrc.2022.128381.1042

[42] Ajith, B. S., Math, M. C., Manjunath Patel, G. C., and Parappagoudar, M. B. (2021). Engine performance and exhaust emissions of Garcinia gummi-gutta based biodiesel–diesel and ethanol blends. SN Applied Sciences, Vol. 3, No. 5, pp 1–11. https://doi.org/10.1007/S42452-021-04537-0/FIGURES/4

[43] Das, A. K., Hansdah, D., and Panda, A. K. (2021). Thermal balancing and exergetic performance evaluation of a compression ignition engine fuelled with waste plastic pyrolytic oil and different fuel additives. Energy, Vol. 229, pp 120629.

https://doi.org/10.1016/J.ENERGY.2021.120629

[44] Gad, M. S., Abu-Elyazeed, O. S., Mohamed, M. A., and Hashim, A. M. (2021). Effect of oil blends derived from catalytic pyrolysis of waste cooking oil on diesel engine performance, emissions and combustion characteristics. Energy, Vol. 223, pp 120019. https://doi.org/10.1016/J.ENERGY.2021.120019

[45] Afzal, A., Soudagar, M. E. M., Belhocine, A., Kareemullah, M., Hossain, N., Alshahrani, S., … Mujtaba, M. A. (2021). Thermal Performance of Compression Ignition Engine Using High Content Biodiesels: A Comparative Study with Diesel Fuel. Sustainability 2021, Vol. 13, Page 7688, Vol. 13, No. 14, pp 7688. https://doi.org/10.3390/SU13147688

[46] Pandhare, A. and Padalkar, A. (2013). Investigations on Performance and Emission Characteristics of Diesel Engine with Biodiesel (Jatropha Oil) and Its Blends. Journal of Renewable Energy, Vol. 2013, pp 1–11. https://doi.org/10.1155/2013/163829

[47] Chiatti, G., Chiavola, O., Recco, E., Chiatti, G., Chiavola, O., and Recco, E. (2017). Effect of Waste Cooking Oil Biodiesel Blends on Performance and Emissions from a CRDI Diesel Engine. Improvement Trends for Internal Combustion Engines. https://doi.org/10.5772/INTECHOPEN.69740

[48] Shirneshan, A. (2013). HC, CO, CO_2, and NO_x Emission Evaluation of a Diesel Engine Fueled with Waste Frying Oil Methyl Ester. Procedia - Social and Behavioral Sciences, Vol. 75, pp 292–297. https://doi.org/10.1016/J.SBSPRO.2013.04.033

[49] Diesel Emissions: Types and Effects of Diesel Engine Emissions. (n.d.). Retrieved January 27, 2023, from https://rentar.com/diesel-emissions-types-effects-diesel-engine-emissions/

[50] Shrivastava, N., Shrivastava, D., and Shrivastava, V. (2018). Experimental investigation of performance and emission characteristics of diesel engine using Jatropha biodiesel with alumina nanoparticles. International Journal of Green Energy, Vol. 15, No. 2, pp 136–143. https://doi.org/10.1080/15435075.2018.1428807

[51] Uttamrao, K. N. and Premkartikkumar, S. R. (2022). Comparative investigation of fly ash-coated semi-adiabatic diesel engine on performance and emission characteristics by using cotton seed biodiesel and emulsified cotton seed biodiesel. International Journal of Ambient Energy, Vol. 43, No. 1, pp 3695–3711. https://doi.org/10.1080/01430750.2020.1840433

[52] Lu, A., Zhang, C., Ji, P., and Li, Y. (2021). Effect of gasoline additive on combustion and emission characteristics of an n-butanol Partially Premixed Compression Ignition engine under different parameters. Scientific Reports, vol. 11, no. 1, pp 1904. https://doi.org/10.1038/S41598-021-81490-3

[53] Liu, Z., Sun, P., Du, Y., Yu, X., Dong, W., and Zhou, J. (2021). Improvement of combustion and emission by combined combustion of ethanol premix and gasoline direct injection in SI engine. Fuel, 292, 120403. https://doi.org/10.1016/j.fuel.2021.120403

[54] Kalaimurugan, K., Karthikeyan, S., Periyasamy, M., Mahendran, G., and Dharmaprabhakaran, T. (2019). Performance, emission and combustion characteristics of RuO_2 nanoparticles addition with neochloris oleoabundans algae biodiesel on CI engine. Energy Sources, Part A: Recovery, Utilization and Environmental Effects. https://doi.org/10.1080/15567036.2019.1694102

[55] Bandhu, D., Djavanroodi, F., Shaikshavali, G., Vora, J. J., Abhishek, K., Thakur, A., … Attarilar, S. (2022). Effect of Metal-Cored Filler Wire on Surface Morphology and Micro-Hardness of Regulated Metal Deposition Welded ASTM A387-Gr.11-Cl.2 Steel Plates. Materials 2022, Vol. 15, Page 6661, Vol. 15, No. 19, pp 6661. https://doi.org/10.3390/MA15196661

[56] Abed, K. A., Gad, M. S., El Morsi, A. K., Sayed, M. M., and Elyazeed, S. A. (2019). Effect of biodiesel fuels on diesel engine emissions. Egyptian Journal of Petroleum, Vol. 28, No. 2, pp 183–188. https://doi.org/10.1016/J.EJPE.2019.03.001

[57] Hoekman, S. K. and Robbins, C. (2012). Review of the effects of biodiesel on NO_x emissions. Fuel Processing Technology, Vol. 96, pp 237–249. https://doi.org/10.1016/J.FUPROC.2011.12.036

[58] Alsultan, A. G., Asikin Mijan, N., Mansir, N., Razali, S. Z., Yunus, R., and Taufiq-Yap, Y. H. (2021). Combustion and Emission Performance of CO/NOx/SOxfor Green Diesel Blends in a Swirl Burner. ACS Omega, Vol. 6, No. 1, pp 408–415. https://doi.org/10.1021/acsomega.0c04800/asset/images/medium/ao0c04800_m001.gif

[59] Praveena, V. and Martin, M. L. J. (2018). A review on various after treatment techniques to reduce NOx emissions in a CI engine. Journal of the Energy Institute, Vol. 91, No. 5, pp 704–720. https://doi.org/10.1016/j.joei.2017.05.010

[60] Sekar, M., Praveenkumar, T. R., Dhinakaran, V., Gunasekar, P., and Pugazhendhi, A. (2021). Combustion and emission characteristics of diesel engine fueled with nanocatalyst and pyrolysis oil produced from the solid plastic waste using screw reactor. Journal of Cleaner Production, Vol. 318, pp 128551. https://doi.org/10.1016/J.JCLEPRO.2021.128551

[61] Murugan, S., Ramaswamy, M. C., and Nagarajan, G. (2008). Performance, emission and combustion studies of a DI diesel engine using Distilled Tyre pyrolysis oil-diesel blends. Fuel Processing Technology, Vol. 89, No. 2, pp 152–159. https://doi.org/10.1016/J.FUPROC.2007.08.005

[62] McCormick, R., Williams, A., Ireland, J., Brimhall, M., and Hayes, R. (2006). Effects of Biodiesel Blends on Vehicle Emissions: Fiscal Year 2006 Annual Operating Plan Milestone 10.4.

[63] Callegari, A., Bolognesi, S., Cecconet, D., and Capodaglio, A. G. (2020). Production technologies, current role, and future prospects of biofuels feedstocks: A state-of-the-art review. Critical Reviews in Environmental Science and Technology, Vol. 50, No. 4, pp 384–436. https://doi.org/10.1080/10643389.2019.1629801

[64] Abdullah, M. F. E., Zhing, S. S., and Bugik, C. B. (2017). Biodiesel unsaturation degree effects on diesel engine NO_x emissions and cotton wick flame temperature. MATEC Web of Conferences, Vol. 90, pp 01041. https://doi.org/10.1051/MATECCONF/20179001041

[65] Roy, M. M., Wang, W., and Alawi, M. (2014). Performance and emissions of a diesel engine fueled by biodiesel–diesel, biodiesel–diesel-additive and kerosene–biodiesel blends. Energy Conversion and Management, Vol. 84, pp 164–173. https://doi.org/10.1016/J.ENCONMAN.2014.04.033