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EXPERIMENTAL INVESTIGATION AND OPTIMIZATION OF BRAKE MEAN EFFECTIVE PRESSURE OF SPARK IGNITION ENGINE FUELLED WITH PYROOIL BLEND

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ABSTRACT:

Plastic is a versatile and widely used material that has had a profound impact on various aspects of our lives. Despite its benefits, the widespread use of plastic has led to environmental challenges, particularly related to plastic waste and pollution. Improper disposal and the presence of non-biodegradable plastics in ecosystems pose significant environmental problems. Efforts are being made to develop more sustainable and environmentally friendly alternatives to traditional plastics, such as biodegradable plastics and improved recycling systems, to mitigate the negative impacts of plastic use. But the waste plastics on the land and sea damage the environmental system. Pyrolysis is one of the effective methods, being concentrated to manage the waste plastics to convert useful products without affecting the environment. Recent research focused on the usage of the liquid phase of pyrolyzed output in Internal Combustion (IC) engines as alternate of blended with conventional fossil fuels. In this research, virgin High-Density Polyethylene (HDPE) oil is pyrolyzed and distilled until 170ºC. The distilled pyrooil is used in different proportions (2, 4, 6 and 8% (v/v)) with conventional gasoline to evaluate its effect on the Brake Mean Effective Pressure (BMEP) in a four-stroke Spark Ignition (SI) engine under different speed and load conditions. With the aid of ANOVA, the most common statistical optimization tool, the optimum value of BMEP was achieved. The results revealed that the 4% of HDPE pyrooil with 96% gasoline blend yields the comparable BMEP of 8.7 bar as gasoline at 3002 rpm and 12.27 Nm load.

***Keywords*:** High-Density Polyethylene, Spark Ignition Engine, Pyrolysis, Brake Mean Effective Pressure.

INTRODUCTION:

Plastic products are lightweight, durable, and resistant to moisture, making them convenient for packaging and transportation of goods. As it has attractive design versatility, cost and energy efficiency, its uses in industries and the day today life is unavoidable[1–3].The production increases exponentially every year since the demand increase. After the invention of first plastic, the Bakelite in 1907, a revolutionary growth occurred in the plastic industries. Plastics are versatile materials categorized into diverse types based on their chemical composition and properties such as Polyethylene Terephthalate (PET or PETE), High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Polyvinyl Chloride (PVC), Polypropylene (PP), Polystyrene (PS). These plastics have distinct properties that make them suitable for different applications in industries such as packaging, automotive, electronics, textiles, and healthcare etc[4].

Among all types of plastics, polyethylene is a commonly used and high-production plastic [5]**.** As per Statista report (November 2023) and Organisation for Economic Co-operation and Development (OECD) (2023)**,** global plastic garbage production in 2019 was expected to have reached 353 million metric tons. Only 33 million metric tons, or 9%, of the 55 million metric tons that were collected for recycling were recycled. 82 million metric tons of plastic waste were mishandled and left lying around, accounting for half of the world's plastic waste that year. In 2022, the global thermoplastic polyethylene market had a volume of around 110.13 million metric tons (Statista, 2023). When plastic garbage is not managed properly, it often spills into rivers, oceans, and other bodies of water, destroying ecosystems and marine life. Plastics with a lifespan of less than five years account for about two thirds of plastic garbage; packaging, consumer products, and apparel and textiles account for 40%, 12%, and 11% of the waste, respectively. Only nine percent of plastic garbage is recycled, while nineteen percent is burned. Approximately fifty percent of it ends up in landfills, and twenty-two percent escapes waste management systems to wind up in wild dumps, open fires, or land and sea habitats. Once generated, plastic persists for extensive periods, spanning hundreds or even thousands of years, resulting in environmental pollution and endangering wildlife, including humans. Contrary to organic materials, plastics do not decompose in the same manner. Instead, they gradually fragment into increasingly smaller particles known as microplastics and nanoplastics. Despite their diminutive size, these minute plastic fragments pose significant hazards and have infiltrated various levels of the food chain, impacting marine organisms and human health alike [4][6]. Plastics contaminate not just the land and air but also have an impact on water sources. It is difficult to accurately determine the annual count of marine animals affected by plastic pollution due to many cases going unreported [7]. However, as indicated by a December 2022 report from Recycle Track System (RTS), a U.S.-based waste and recycling management company focused on environmental conservation, estimated over 1 million marine creatures, particularly sea turtles, succumb annually to the effects of plastic pollution in the ocean. So, it is most urge to manage the waste plastics via converting them to some useful products without affecting the environment. There are several advantages to converting plastic into energy such as Resource Utilization, Energy Generation, Waste Reduction, Lower Greenhouse Gas Emissions from incineration, Energy Security, Circular Economy, and Employment Opportunities[8]. Therefore, effectively, and productively utilizing plastic waste could offer a feasible solution to this problem.

Plastics, which primarily consist of carbon and hydrogen molecules derived from petroleum crude oil [9]. pose environmental hazards when discarded, incinerated, landfilled, or dumped in oceans, affecting both the environment and aquatic life negatively. Given that most plastics are composed of hydrocarbons, there exists the potential for greater energy extraction, achievable through both mechanical and chemical recycling methods[10]**.** Mechanical recycling, being the more cost-effective option, encompasses two effective processes: gasification and pyrolysis [11]. Gasification proves advantageous when producing gaseous by-products, whereas pyrolysis stands as the optimal choice for generating solids and liquids [12]. The chemical process of pyrolysis involves heating organic compounds to elevated temperatures without the presence of oxygen. This process produces a combination of gases, liquids, and solids by breaking down the plastic materials into simpler chemical molecules [13]**.** Researches indicate that pyrolysis demonstrates a high capacity to efficiently convert polyethylene and various polymer wastes into volatile compounds [14]. The breakdown of plastics by thermal or thermochemical by using a catalyst. In the thermal pyrolysis researchers trying to use different reactors like fixed bed- batch and continuous reactors, moving bed - mechanical and fluidized bed reactors etc. [15]**.** During catalytic pyrolysis, researchers use different catalysts like Zeolite, ZnO, Gamma Aluminium, Dolomite etc [16]. In all type of pyrolysis, the yielding of liquid oil depends mainly on temperature, reaction time, retention time, type of biomass, type of reactor etc [17].

The engine performance is related how best work output will be got with lower fuel consumption and emission. This is measured by numerous factors like brake thermal efficiency(BTE), brake power(BP), specific fuel consumption(SFC), exhaust gas temperature(EGT),brake mean effective pressure(BMEP), volumetric efficiency(VE), etc. The fuel quality plays a key role for all these properties in an existing engine. This paper deals the BMEP variation with respect to different blending ratio off HDPE oil with gasoline in a SI small scale testing engine during different speed and load conditions. The BMEP is used to assess how well an engine is operating as well as to compare other engines of the same type with differing engine capacities. The BMEP specifies the quantity of brake power produced per unit volume of engine displacement, making it a criterion for comparing engines of many sizes and cylinder counts. The volumetric efficiency of the engine, the density of the intake charge, the compression ratio, and other variables affect the BMEP.

Response surface methodology is used to model and optimize the responses and the associated factors. The goal of the RSM technique is to design experiments to produce sufficient and trustworthy measures of the answer, creating the best-fitting mathematical model for the data discovered from the experimental layout, and figuring out the ideal value for each of the independent factors that results in greatest or lowest value that the answer can have[18]. Design of Experiments (DoE) tools are statistical techniques that aid in comprehending the role that individual and combination input elements have on the output (responses). Using the ideas of Box-Behnken Design (BBD), Fractional Factorial Design (FFD), Central Composite Design (CCD), and Plackett-Burman, the DoE approaches are frequently utilized to construct experimental designs[19]. Box-Behnken often has fewer design points, which makes it easier to forecast the first- and second-order coefficients efficiently. BBD can therefore be less expensive and time-consuming. Each factor requires three levels of BBD, which is rotatable. The response surface design's complete quadratic model is compatible with the BBD. When

doing experiments with more than two variables and when the optimum is anticipated to lie in the middle of the factor ranges, this experimental design should be taken into consideration[20].

Onwudili et al. (2009) pyrolyzed LDPE and PS in a batch reactor separately and mixed. The LDPE starts to yield the oil at 450ºC and PS at 350ºC. The mixed LDPE and PS with ratio of 7:3 yields the oil at 350 ºC and the result revealed that the mixture of LDPE and PS yields more oil than the individuals[21]. Ahmad et al. (2020) use liquefaction technique to produce liquid fuel from PS using ethanol as a solvent. They draw conclusions from the experiment that the maximum liquid yield of 84.7% (wt) was recorded at 350 °C, with a 0.5:1 ethanol to polystyrene ratio and a 60-minute reaction duration[22]. Aisien et al. (2021) done pyrolysis with and without catalysts in batch reactor by using PP plastics up to 400 ºC with the heating rate of 15 °C/min. For catalytic pyrolysis, the FCC catalyst was used up to 10%(wt.). The results shows that the thermal pyrolysis yields maximum liquid yield about 83.3 %, while the catalytic pyrolysis yields about 77.6% with 0.1% of catalyst. Some researches concentrate on using plastics in co-pyrolysis concept with other biomasses[23]. Mishra & Mohanty (2020) done co-pyrolysis on mahua seeds with waste plastics (PS) in different blending ratio in semi-batch reactor up to 550 °C, with 80 °C/ min heating rate in Nitrogen atmosphere. According to the findings, thermal pyrolysis of individual mahua seeds produced less liquid than when waste plastics were blended at a weight percentage of 20. Additionally, the analysis demonstrated a decrease in viscosity, oxygen concentration, and moisture, while an increase in heating value, carbon content, and acidity were discovered[24].

Hossain et al. (2019) used rice straw with different compositions and waste PE plastics to create liquid fuel through the co-pyrolysis idea. In a fixed bed reactor, the pyrolysis was conducted between 400 and 500 ºC. At 430 ºC, they obtained the greatest liquid yield. around 61% (wt.) for a 1:1 mixing ratio. For each individual feed of polythene and rice straw, about 80% (wt.) and 35% (wt.) of liquid were produced, demonstrating that the amount of rice straw in the combination reduces the liquid yield.[25]. In a bench-scale reactor, Parku et al. (2020) investigated the effects of heating rate and vacuum conditions, generating 81% to 93% (wt.) of the product. They came to the conclusion that heating rate influences the distribution of product composition under vacuum pyrolysis.[26]. Kumari & Kumar (2017) examined the impact of reactor pressure on the pyrolysis of waste HDPE. They discovered that HDPE degrades more aromatically around 410–430 °C and under pressures between 11 and 36 bar, which makes it more suitable for use as fuel.[27].Researchers looked at how temperature, heating rate, and particle size affected fuel characteristics and the percentage of oil yield. The results showed that lowering the heating rate shortens the time it takes for plastic to degrade, raising the temperature accelerates the evaporation process, and producing more oil faster from smaller plastic pieces[28]. Ndiaye et al., (2023) pyrolyzed the mixed plastics (HDPE, LDPE, PP &PET) in different ratios through thermal and catalytic pyrolysis. The collected 13 % and 15.16% liquid fuel type oil in Thermal and Catalytic pyrolysis, respectively. As per GC-MS analysis, they documented that extracted oil has the carbon range of C_8-C_{40}, 43.175 MJ/kg heating value from catalytic pyrooil and other properties are as comparable with diesel[29].

From the analysis of literature, the researchers confirm that HDPE and LDPE plastics have the potential to produce liquid fuels and it could be used in IC engines and power generation units of heavy machinery industries. It is the smart way that the major potential for dumping of waste plastic is reduced and used as fuels which will reduce the usage of fossil

fuels. Also form the previous research outputs, the oil or wax can be extracted from plastics by pyrolysis and by further process like distillation, it can be used as a substitute of conventional fuels in IC engines. This research focuses on utilizing pyrooil from waste HDPE in spark ignition engine to examine brake mean effective pressure (BMEP). The pyrooil was blend with regular gasoline at various percentages from 2 to 8% and evaluated in SI engine. This will reduce the filling of land yards, reduces pollution on the environment, and reduces the dependence on fossil fuels by using waste plastic as a source of producing pyrooil.

MATERIALS AND METHODS:

Pyrolysis of waste HDPE:

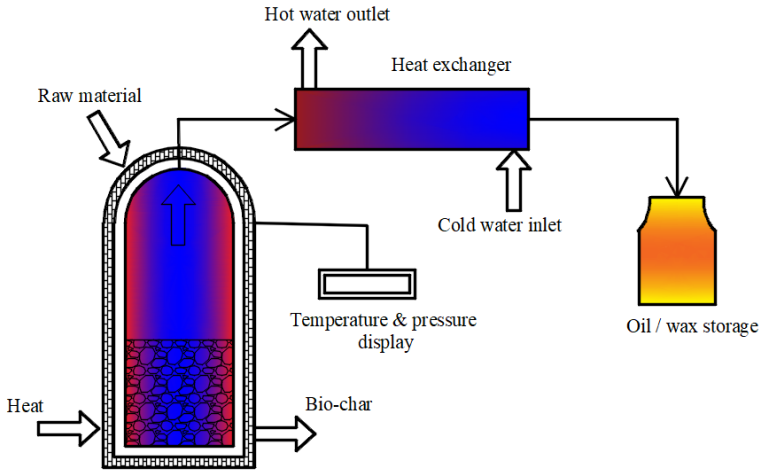

Figure 1. Experimental setup for pyrolysis of waste HDPE

Figure 1 shows the schematic diagram of the experimental setup of pyrolysis with the key facilities of the pyrolysis unit like heating unit, heat exchanger, temperature and pressure sensors, insulator, oil/wax storage bottle, and gas exit path. An insulated fixed bed batch reactor on a laboratory scale was fabricated in the University premises. The reactor has diameter of 55 cm and height of 86 cm, has a volume of approximately 200 L.

The reactor was heated by an LPG-fuelled conventional furnace. The firing was accelerated by compressed air. The temperature and pressure were monitored from sensors located in the reactor**.** The furnace was heated up to 450ºC with a slow heating rate. The hot gases from the reactor were passed through a coil-type heat exchanger to liquify them. Up to 350ºC, there was only gaseous output was noticed. Above the 350ºC temperature inside the reactor, the wax-type output starts to fill the container. When the temperature increases, the output increases up to 425ºC, beyond that the wax output drops significantly, and gaseous output increases. The maximum amount of wax was collected between 400-425ºC which is around 70% of the total output.

The wax output of pyrolysis is distilled in a simple laboratory-scale distillation unit. A sample of 0.5 Lit wax was heated up to 170ºC in the distillation unit counter flow heat exchanger as condenser. At 52ºC, the oil started to drop, and it continued up to 170°C. The distilled oil was tested for important properties and observed that its properties are comparable with gasoline [30].

Engine performance test of pyrooil prepared from waste HDPE:

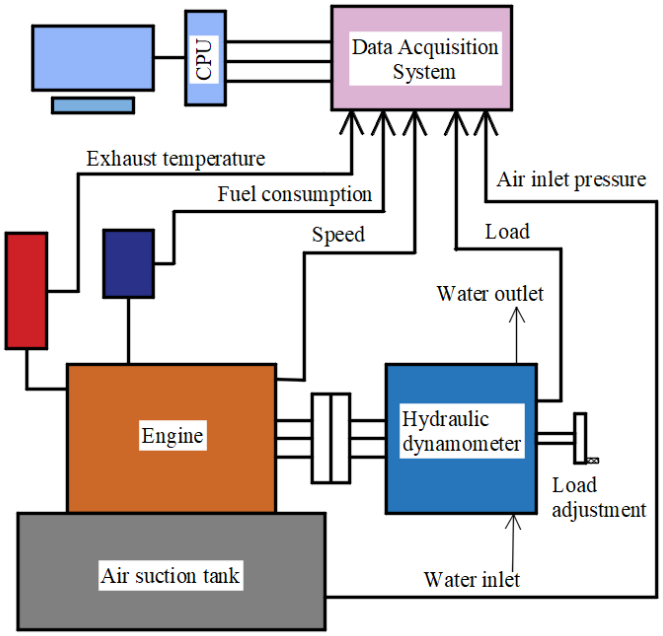

Figure 2. Experimental setup for engine performance test of pyrooil prepared from waste HDPE.

The distilled oil was blended as 2% 4%,6% and 8% ratio with conventional gasoline. Initially the engine was assessed with conventional M91 gasoline under differ load and speed conditions. The engine has the following specification, as listed in Table 1.

Table 1. Specification of engine used for performance test.

Engine Parameter	**Specification**
Engine type	Naturally aspirated engine
Engine capacity	208 cc
No. of cylinders	1
Absolute Maximum Power	5.2 kW at 3600 rpm
Net Power	4.5 kW at 3600 rpm
Net Torque	12.5 Nm at 2800 rpm
Cooling	Air cooled
Loading	Hydraulic Dynamometer

The values of outputs like, BTE, BP, SFC, A/F ratio, BP, and Volumetric Efficiency (VE) are calculated by the software based on the input values like speed, torque, intake air pressure & temperature, exhaust gas temperature, and the heating value of the fuel. Once the experimental over with conventional gasoline, then the fuel line and the tank was drained completely, then the next blend of oil is evaluated.

RESULTS AND DISCUSSION:

One-factor-at-a-time approach for optimization of BMEP:

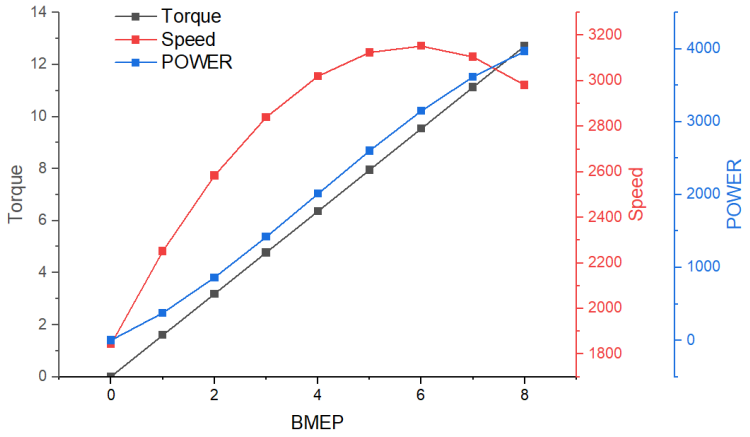

Figure 3. BMEP Vs Torque, Speed, Power

Figure 3 shows the relationship between torque, speed, and power with conventional gasoline. The torque and BMEP has a liner relationship since the BME is a function of torque only. During idealing, the speed and torque was set as 1843.6 rpm and 0.0123 N.m respectively and the BMEP was 0.0007431 bar. The speed has no influence on BMEP. The power is influenced by both torque and speed as shown in the Equations 1 and 2. The brake mean effective pressure of the engine is given by,

$BMEP=2\pi T.n/V_d$ (1)

$BP=2\pi NT/60$ (2)

where T = Torque at the crankshaft, N.m, n=number of revolutions per power stroke,
N= Crank shaft rotational speed, rpm, V_d = Engine displacement, m^3.

From the graph, it can be noticed that when the speed start to decrease, the is notable change in the power. So, for a particular power, gaining of torques lead to loosing of speed. This indicates BMEP is higher at maximum torque than maximum power due to the engine's capacity for work being the greatest when burning the most fuel, which occurs at peak torque. During the experiment, the engine developed maximum of 7.0 bar BMEP and at 3970 W power during 12.71 Nm torque, 2980 rpm speed, gasoline as fuel.

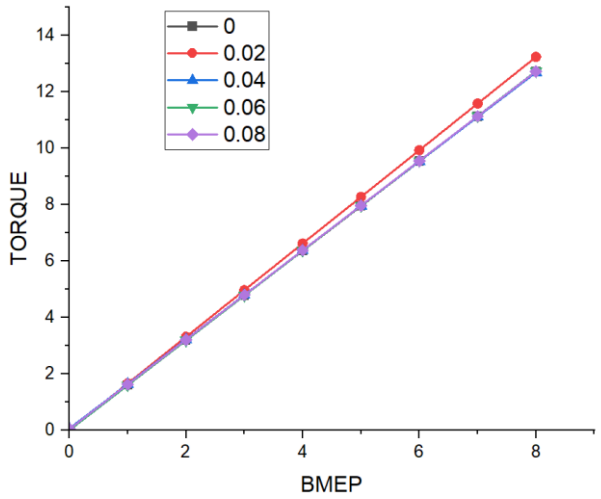

Figure 4. BMEP Vs Torque

The influence of torque produced by different blending in the BMEP is shown in Figure 4. At low load conditions, all blends produced the similar BMEP. During part and higher load, for 2% blend produced more torque for the same BMEP. The remaining blending shows almost same results as gasoline.

The speed doesn't have any effect on BEMP. But during the experiment, when the load increases, the speed decreases for a particular power. This is indicted in Figure 5. The graph shows the different speed of operations for different blending ratios with different loads.

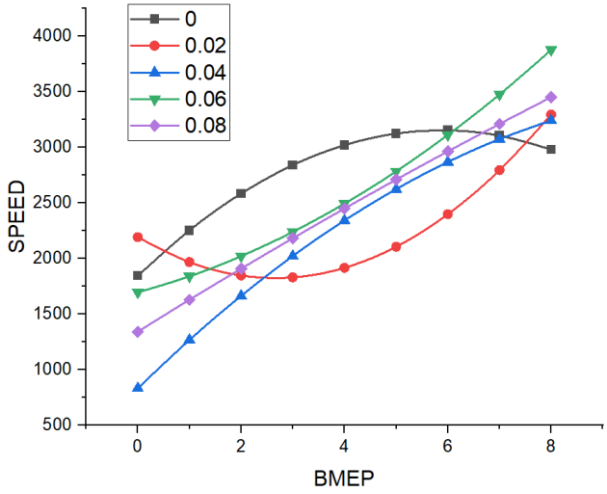

Figure 5. BMEP Vs Speed

The engine was operated at different speed ranges for different blending ratio as 1843-3152, 1829-3294, 841-3241, 1694-3877, 1340-3452 rpm for 0%, 2%, 4%, 6% and 8% respectively. From the graph 2, it was notified that the torque on crank shaft is more for 2% blend, so the speed is proportionally changing for producing power. The maximum BMEP 8 bar was produced by pure gasoline during 2981rpm speed at 12.71 Nm torque. The same BMEP was produced at 3877 rpm speed and 12.73 Nm torque by 6% blend. Form these two values, it can be noticed that apart from the torque, the other factors like heating value, A/F ratio also influence the BMEP. Brake power is the combined effect of speed and torque. Graph 4 shows the power developed in different blending operations under varying speeds and load.

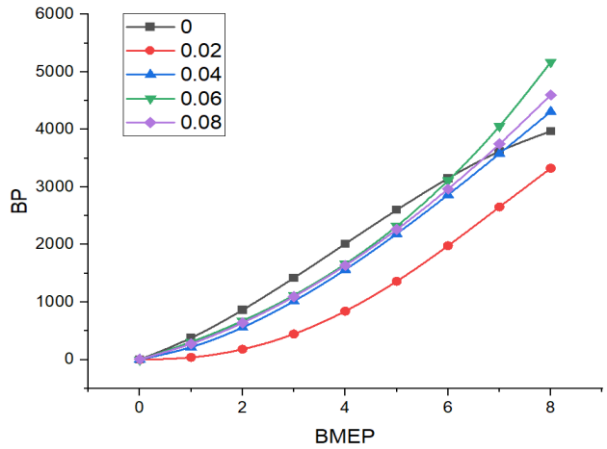

Figure 6. BMEP Vs Brake Power

From the Figure 6, it can be evaluated that at the maximum BMEP 8 bar, 3969, 3325,4309,5170,4600W power was developed by 0%, 2%, 4%, 6% and 8% respectively. The 2% blend developed lowest power and 6% blend produced the maximum power for the same BMEP value(8 bar). At low and medium level BMEP values, the 0%(pure gasoline) blend dominates for power production especially up to 6 bar BMEP. The engine's power and fuel energy supply rate are directly correlated with BMEP and BTE[31]. The experimental results prove that the heating value of the blended fuel also plays a vital role in engine performance. To optimize the varied factors to get maximum BMEP, a statistical analysis methodology, Response Surface Method is used. A theoretical experimental model was designed based on the experimental values, using the Box-Behnken Design(BBD), and evaluated. ANOVA, Analysis of variance tool is used to optimize the variables and the solution was revealed.

Response surface methodology approach for optimization of BMEP:

A BBD matrix was created to alter three factors. To lessen the impact of inexplicable variation in the observed response brought on by unrelated variables, all experiments were conducted at random. The outcomes of the tests were fitted to a quadratic polynomial model to forecast the system reaction, which is provided by Equation (3).

$$Y=\alpha_0 + \alpha_1 A + \alpha_2 B + \alpha_3 C + \alpha_4 AB + \alpha_5 BC + \alpha_6 AC + \alpha_7 A^2 + \alpha_8 B^2 + \alpha_9 C^2 \quad (3)$$

where Y is BMEP (response), α_0 is intercept (constant), α_1, α_2, and α_3 are linear co-efficient, α_4, α_5, and α_6 are interactive co-efficient, α_7, α_8, and α_9 are quadratic co-efficient, A, B, C are speed, torque, and blend %, respectively.

Table 2. Independent variables and their coded values

Factor	Name	Units	Coded Values		
			-1	**0**	**+1**
A	Speed	Rpm	2700.00	2916.50	3133.00
B	Torque	Nm	3.90	8.10	12.30
C	Blend	%	0.00	4.00	8.00

For any BBD design, the number of runs required is 2K(K-1)+C where, K is number of factors and C= number of centre points. In this BBD experimental design, 3 factors with 3 levels are used. The number of runs is 2*3(3-1)+3=15. Analysis of Variance was performed for three input variables in the engine performance test. Speed & torque are conditional variables and blending ratio is fuel used for testing. The influence of these variables was analysed with respect to the engine BMEP output. The lowest and highest speed range were taken as 2700 and 3133 rpm respectively whereas the minimum and maximum torque was 3.90 and 12.3 Nm, respectively. The blending ratio used in the engine was 0 to 8 % with 2% increment as shown in **Table 2.** The experiment was modelled with three level, three variable with 15 runs. The actual and predicted values of the response are shown in **Table 3.**

Table 3. BBD Experimental design for BMEP response

		Factor 1	Factor 2	Factor 3	Response 1 (Actual)	Response 1 (Predicted)
Std	Run	A:Speed (rpm)	B:Torque (Nm)	C:Blend (%)	BMEP (bar)	BMEP (bar)
10	1	2916.5	12.3	0	7.75	7.67

7	2	2700	8.1	8	4.1	4.30
8	3	3133	8.1	8	5.07	4.53
15	4	2916.5	8.1	4	6.1	6.16
3	5	2700	12.3	4	8.7	8.54
6	6	3133	8.1	0	5.07	5.28
13	7	2916.5	8.1	4	6.1	6.16
12	8	2916.5	12.3	8	6.75	6.92
11	9	2916.5	3.9	8	1.44	1.61
5	10	2700	8.1	0	5.1	5.05
1	11	2700	3.9	4	3.4	3.24
9	12	2916.5	3.9	0	2.44	2.36
14	13	2916.5	8.1	4	6.1	6.16
4	14	3133	12.3	4	8.7	8.78
2	15	3133	3.9	4	3.4	3.47

The fitness of the theoretical design can be evaluated by R^2, Predicted R^2 and Adjusted R^2.The R^2 (goodness of fit) is the coefficient of determination known, equal to ratio between the total sum of squares around the mean and the sum of squares explained by a regression model. In this model, R^2 value is 99.20% which is close to 1. Predicted R-squared and adjusted R-squared employ distinct strategies to counteract the desire to add more. A model with too many terms can yield unreliable results, thus the protection that adjusted R-squared and predicted R-squared offer is essential. The regression model's appropriate number of independent variables is included with the aid of these statistics. From **Table 4,** the adj. and predicted R^2 values are identified as 98.40%, and 95.95% respectively with Adequate precision of 36.0367. An adequate precision greater than 4 is desirable which good enough signal.

Table 4. Fit statistics of the model

Std. Dev.	0.2722	**R^2**	0.9920
Mean	5.35	**Adjusted R^2**	0.9840
C.V. %	5.09	**Predicted R^2**	0.9595

The statistical information about the importance of a range of factors and how they interact with the ANOVA-provided trial results is shown in **Table 5.** The total statistical analysis of the model is presented in the first row. Sum of Squares, degree of freed, Mean Square are displayed as 64.48,7,9.21, respectively. F-value is the ratio of two variances. It shows how the variance within groups relates to the variance between groups. A high F-value indicates that there is more variation in group means than would be predicted. When analysing an ANOVA, the P-value indicates the probability of receiving an F-value as high as the one obtained from the sample data, assuming that the null hypothesis is true. There may be sufficient evidence to reject the null hypothesis if the P-value is small, less than 0.05. From table 3, it is indicated

that the Model F-value is 124.27 which implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Since P-value is less than 0.0001, the model terms are more significant. The subcategory "Lack of Fit Row" assesses how well the model and the data fit together. It shows that Sum of Squares as 0.5188; Degrees of freedom as 5; Mean Square as 0.1038 which shows the model fitted well with the data.

Table 5. ANOVA for reduced quadratic model of BMEP.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	64.48	7	9.21	124.27	< 0.0001	significant
A-Speed	0.1105	1	0.1105	1.49	0.2617	
B-Torque	56.29	1	56.29	759.42	< 0.0001	
C-Blend %	1.12	1	1.12	15.18	0.0059	
AB	0.0000	1	0.0000	0.0000	1.0000	
BC	0.0000	1	0.0000	0.0000	1.0000	
B^2	0.0862	1	0.0862	1.16	0.3167	
C^2	6.94	1	6.94	93.69	< 0.0001	
Residual	0.5188	7	0.0741			
Lack of Fit	0.5188	5	0.1038			
Pure Error	0.0000	2	0.0000			
Cor Total	65.00	14				

The relation of the Speed, torque, and blending ratio with the BMEP is given by the coded quadratic equation as follows.

BMEP= $+6.16+0.1175A+2.65B-3750C-0.1523B^2-1.37C^2$, where A is Speed, B is Torque and C is Blending ratio. The intercept value is positive; two linear coefficients are positive; quadratic coefficients are negative. This satisfies for maximization of the BMEP output.

Surface diagrams of RSM are a terrific way to see the intricate relationship between a response variable and input elements. These diagrams provide researchers with a visual representation of how changes to the input parameters impact the associated response. These diagrams can show several patterns, such as upward or downward slopes, spikes, or troughs, which represent the complexity of the system, depending on the properties of the reaction or process being studied. The ability of RSM surface diagrams to identify ideal input settings and improve comprehension of variable interactions is its main advantage. By examining the graphical representation, researchers can determine the ideal combination of input parameters that maximize the desired outcome. In many academic fields, this data is crucial for making decisions and streamlining procedures[32]. The surface diagram in **Figure 7** shows the effect of speed and torque on BMEP. The range of speed is 2700 to 3183 rpm in one axis and the torque range is 3.9 to 12.3 Nm in another axis. The response BMEP is fixed in another axis from 0 to 8%. The maximum BMEP occurs at high torque zone for all blending. Also, it can be to be noticed that the torque and BMEP have a linear relationship.

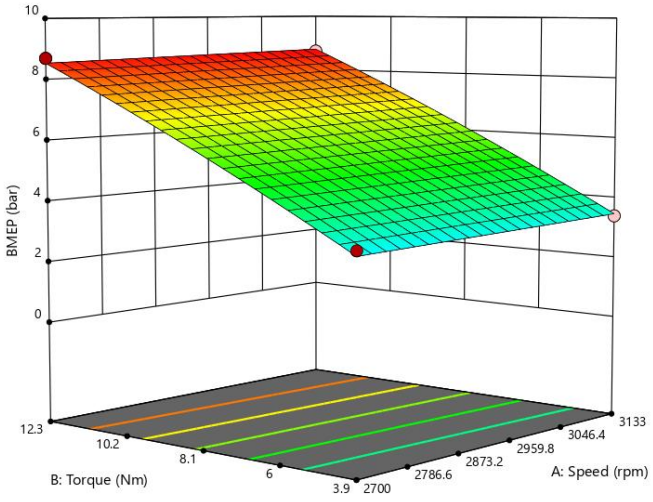

Figure 7. Surface diagram

From the Figure 8, it is revealed that the optimum values of the factors are 3002.37 rpm speed, 12.2701 Nm torque, 3.58195 blend ratio for maximum of 8.7 bar BMEP. This work successfully evaluates and quantifies the impacts of various input factors on the BMEP of the SI engine using RSM-based surface diagrams. The graphical portrayal of these relationships aids in the process of making well-informed decisions about engine input parameters and BMEP optimization.

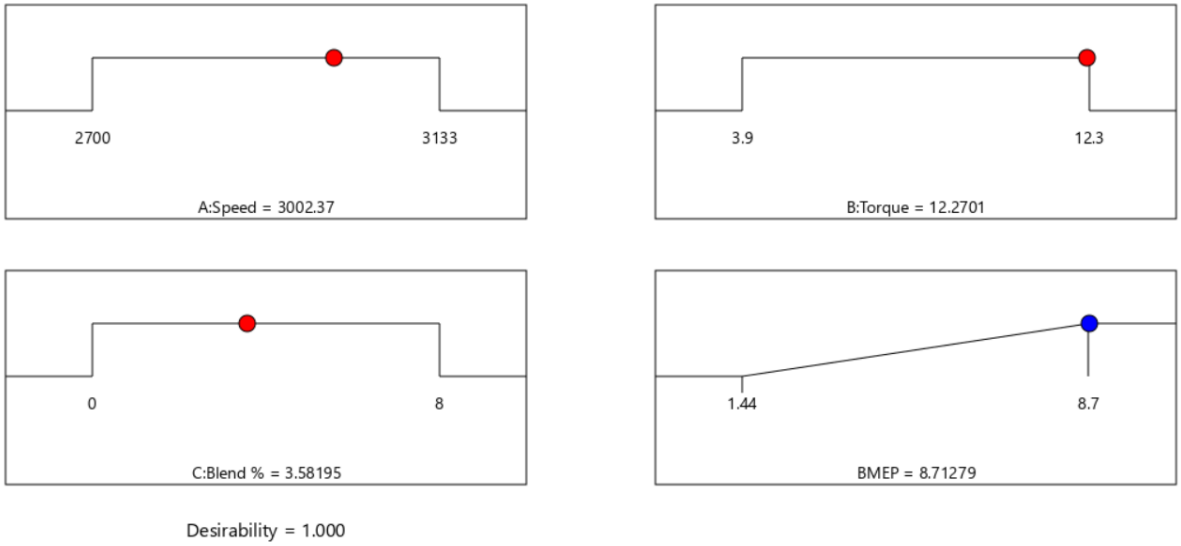

Figure 8. Ramp output

Summary of discussion:

Prurapark et al., conducted a pyrolysis experiment involving HDPE and PET plastics up to a temperature of 450°C. The study's findings indicated that the optimum temperature for producing the best pyrolysis oil was 450°C.The quantity of pyrolysis oil obtained from distillation, based on temperature ranges during the initial sample collection (lower than 65°C, 65–170°C, 170–250°C, and above 250°C), resulted in gasoline, kerosene, and diesel volumes of 60 mL, 90 mL, and 39 mL, respectively[33]. Kumar and Singh conducted thermal pyrolysis

experiments using virgin HDPE within a semi-batch reactor, operating up to 400°C to 550°C, with 20°C/min heating rate. Their findings revealed that at 450°C, the maximum oil yield was obtained. At lower temperatures, highly volatile products were obtained, while temperatures of 500°C and 550°C , viscous liquid and wax were collected. Additionally, they found that as the temperature increased, the reaction time decreased and the contained carbon within the range of C_{10} to C_{20}. This range closely resembles the characteristics of diesel fuel[34]. Qian & Ren(2023) has done a valuable review about the technologies related to transforming plastic into useful products, and optimization of the different parameters associated with the conversion of plastic wastes to byproducts. The study determined that while gasification and pyrolysis are viable processes for converting plastic waste into valuable products, the most convenient approaches in the realm of plastic waste management are Response surface methodology and Superstructure optimization.[35].Through thermal pyrolysis between 450 and 621°C**,** Istoto et al. (2019) produced 3.25 litres of naphtha, 0.85 Liters of gasoline, 0.325 litres of diesel fuel, and 2.9 Liters of gasoline from 5 kg of HDPE polymers[36].

Ghodke et al., conducted pyrolysis experiments involving LDPE, HDPE, PP, as well as a combination of these three virgin plastics. Through this process, they successfully obtained liquid oil with varying weights from different plastics and mixed plastic combinations, with percentages at 500°C as follows: HDPE (64.6wt.%), LDPE (62.2wt.%), PP (63.1wt.%), mixed plastics (68.6wt.%), and domestic waste (64.6wt.%).The characterization techniques such as Fourier Transform Infrared Spectroscopy (FTIR) and GC-MS revealed that a broad spectrum of hydrocarbons within the C_8–C_{20} range were present which are in the range of diesel with other physical and chemical properties comparable with diesel[37]. Hussein et al., conducted an experimental investigation involving thermal and catalytic cracking of various plastic types of HDPE, LDPE, PP, PS, and PET in semi-batch reactor under nitrogen gas atmosphere, 350 to 500°C and residence times of 60, 90, and 120 minutes. They revealed from the GC-MS result that the presence of mainly aromatic and paraffinic hydrocarbons, suggesting potential use as a fuel source[38].

During pyrolysis, the primary output obtained from the condenser, particularly when dealing with HDPE plastics, comprises wax. HDPE, a polymer consisting of extended chains of hydrocarbon molecules, undergoes pyrolysis at elevated temperatures without oxygen, a method used to disintegrate plastics into smaller constituents. This process causes the intricate structure of HDPE molecules to disassemble, resulting in the creation of various smaller hydrocarbon chains and compounds[37]. As HDPE molecules disintegrate under elevated temperatures, typically within the range of a few hundred degrees Celsius, they fragment into smaller entities. Some of these diminished entities combine again to produce substances resembling waxy materials. Throughout pyrolysis, volatile compounds and gases emerge as HDPE decomposes. These emanations may experience cooling and condensation as they progress through the pyrolysis reactor or exit the system. The condensation of these evaporated compounds, which encompass lighter hydrocarbons, can lead to the formation of waxy or oily substances. HDPE plastics may include additives like plasticizers, stabilizers, or lubricants, which could affect the constitution of the pyrolysis byproducts. A few of these additives might contribute to the generation of waxy compounds during the decomposition process. The temperature, duration of residence, and other procedural parameters during pyrolysis can shape the nature and composition of the resultant products.

Salaudeen et al., conducted a pyrolysis process on virgin HDPE plastics up to 500 ºC within a fluidized bed reactor. The findings showed that wax emerged as the primary product of pyrolysis. Introducing olivine into the fluidized bed reactor raised the wax output significantly, from 45.6 to 66% (wt), and promoted the production of olefins. Their research indicated that the resulting pyrolysis wax possesses a high energy content, suggesting its potential as a fuel source[39]. Al-Salem and Dutta conducted a study on the pyrolysis outcomes of HDPE, LDPE, and plastic solid waste (PSW) using a fixed bed reactor, subjecting them to temperatures up to 800 ºC. Their findings highlighted that greater branching in the PE samples led to increased wax collection at 500 °C, with the maximum yield of 64.5 wt % observed from the pyrolysis of LDPE. In contrast, due to its less-branched structure, HDPE yield a lower wax of 32% at 500°C. Nevertheless, HDPE biomass underwent cracking to form gases, subsequently condensed into pyrooils[40]. Luo et al., did an experimental analysis on Wax formation during pyrolysis of HDPE. They did the pyrolysis at 360-420 ℃ in a continues stirred-tank reactor and the concluded that low temperature and short reaction time was not feasible for the pyrolysis of HDPE to wax.[41]

Gaidhani and Mahanwar conducted a process wherein they converted waste LDPE and HDPE into wax through pyrolysis, employing ZSM 5 (a zeolite-based catalyst) and Luperox as catalysts. Their observation revealed that as the catalyst amount and residence time increased, the output of PE wax decreased. Additionally, this escalation resulted in a degradation of the properties inherent to the PE wax[42]. Abdy et al., conducted thermal pyrolysis of HDPE in a fixed bed reactor, in the temperature range between 450–550 °C. They explored the impact of two different nitrogen gas flowrates, 2 and 4 L/min, on the yielding of wax and its chemical properties. Their study aimed to understand the influence of these process parameters and resulting vapor residence times on the outcomes. Notably, this technology demonstrated a remarkable affinity for producing waxes, achieving a high yielding up to 91.87% wax from HDPE at 500 °C, employing with nitrogen gas volume flowrate of 4 L/min and subsequently obtaining a 1.76-second vapor residence time. Increased generation of olefinic wax was reported at higher operating temperatures, which were related to the enhancement of degrading radical mechanisms such as β-scission. [43]. Li et al., investigated to examine how the thickness of the material bed impacts the yield distribution and product composition during the pyrolysis of HDPE within the temperature range of 425–550°C, employing a fixed bed reactor. Their study revealed interesting findings: a higher wax fraction was attained within the thin bed at 425°C. However, as the temperature exceeded 500°C, they observed a shift in product generation, with the thick bed yielding more oil and wax products[44].

Ong et al., conducted pyrolysis experiments on HDPE, LDPE, and PP at 450°C to analyse the resulting output. Their findings indicated the production of waxes from these materials. Through Gas Chromatography-Mass Spectrometry (GCMS) analysis, they observed distinct compositions within the waxes derived from each material. Specifically, the waxes from HDPE and LDPE were composed of paraffin. Conversely, the wax obtained from PP consisted of a blend containing naphthene, isoparaffin, olefin, and paraffin compounds[45]. Some researchers extract waxes from PE and used for some applications. Vargas and Hanandeh conducted research where they utilized wax obtained from PE which is used in industries with bitumen. When virgin bitumen was mixed with 7% PE wax, several positive outcomes were

observed: the softening point increased by 15%, viscosity decreased by 27%, and no segregation issues were noted. Furthermore, this modification resulted in a 32% increase in stiffness and improved resistance to hot climates[46]. Wiriyaumpaiwong and Jamradloedluk conducted fast pyrolysis experiments on plastic wastes, focusing on PE and mixed plastics, across a temperature range of 500-800°C. They collected crude oil because of this process and employed fraction distillation to separate diverse types of oils obtained. The mixed plastic oil was distilled for ninety minutes at 150°C and 180°C, while the PE oil was distilled for sixty minutes at 180°C. Comparing the distillates produced by this method to the original pyrolytic oils, they showed reduced densities and viscosities. Interestingly, the properties of both distillates were identical to those commonly observed in gasoline, suggesting that they shared similar traits[47]. Khan et al., conducted pyrolysis experiments on HDPE within a custom-designed stainless steel laboratory reactor. This process occurred within a temperature range of 330–490°C, aiming to generate valuable fuel products. The maximum oil yield achieved was 77.03% over a duration of 2 hours. The liquid collected from this process exhibited a larger volume and a lower boiling range. Further fractional distillation revealed an increased presence of lighter fractions when subjected to higher temperatures and longer durations. The physical and chemical properties of the pyro fuel oil possess potential utility, allowing for the creation of highly efficient fuel. Blending these products with other conventional fuels can further optimize their functionality[48].

Faisal et al., initiated the process by subjecting HDPE, PP, and PS to pyrolysis to obtain crude oil. Subsequently, they underwent a distillation process, separating the crude oil into specific fractions—gasoline up to 170°C, diesel between 170–380°C, and residue above 380°C. They specifically focused on refining the diesel fraction to create a distilled plastic diesel, which was later evaluated in a diesel engine. Their documentation revealed that the performance of the engine and its emission characteristics showed improvements or similarities when utilizing a blend comprising 15% plastic-derived diesel alongside regular diesel[49]. Sarna et al.,(2022) experimented HDPE oil by varying compression ratio, injection pressure and load in diesel engine and compared the engine performance with diesel. By using Taguchi's method, the optimized Brake thermal efficiency(BTE) and Specific Fuel Consumption(SFC) value achieved at 100% load, 16:1 Compression Ratio with 220 bar Injection Pressure of pure HDPE oil[50]. Padmanabhan et al.,(2022) evaluated the performance of LDPE oil and 15% ethanol additive with diesel in CI engine. Different ratios (20%, 30%, 40%)of LDPE oil and 15% of Ethanol were blended with conventional diesel, to conduct the performance and emission tests. A model was developed by using Full factorial Design(FFD) in the Analysis of Variance(ANOVA) and obtained the 20% LDPE oil with 15% Ethanol as the more suitable for diesel engines with high performance and low emission factors[51]. Kumar Das et al., (2023) blended the PP+HDPE oil with diesel in different proportions and assessed in diesel engines with three variables, engine load (20, 40%, 60, 80, and 100%), compression ratio (16, 17, 18:1), and fuel blend (10, 20, 30, and 40%). Utilizing Response Surface Methodology (RSM), the optimal parameters are 20% plastic oil mixing ratio at full load and an 18:1 compression ratio[52].

Qian and Jingzheng Ren conducted a comprehensive assessment of emerging technologies, highlighting the potential of gasification and pyrolysis in transforming plastic waste into valuable resources. They noted the frequent utilization of RSM for optimizing

parameters in experimental design. They also emphasized how important Superstructure Optimization Frameworks are for directing process synthesis and pathway selection in the conversion of plastic waste. Additionally, the researchers proposed that networks aimed at recycling plastic trash may be more successfully designed by utilizing Multi-Objective Supply Chain and Green Supply Chain Frameworks.[35]. Sajdak and Słowik conducted a study focusing on the impact of process conditions on the properties of outputs derived from the pyrolysis of biomass and plastic waste. Their analysis, employing ANOVA (Analysis of Variance), revealed that the material type significantly influenced the nitrogen presentation within the char, as well as the nitrogen and sulphur concentrations within the liquid fraction. Moreover, the type of material also notably affected the carbon monoxide, carbon dioxide, and methane presence within the gaseous fraction[53]. Mibei et al., conducted experimental and statistical analyses aimed at maximizing pyrolysis output through catalytic pyrolysis involving various plastics and diverse catalyst ratios. Employing optimization techniques such as RSM and Central Composite Design (CCD), their research revealed that polyethylene demonstrated the highest liquid yield, reaching 87.23 wt% at 300ºC using a 10% catalyst ratio[54].

Muzyka and colleagues investigated the influence of different Plastic ratios on the gaseous products obtained from co-pyrolysis. They employed the Box–Wilson Design of Experiments (DOE) concept to optimize these outcomes. Their research showed that co-pyrolysis at 550°C with a 32% addition of a waste plastic combination was the optimum way to maximize the amount of hydrogen and hydrocarbons and also increasing the calorific value of the pyrolysis gas[55]. In the same line of research, Joppert et al., employed a Factorial Design methodology to improve the diesel fuel fraction (C_9–C_{23}) derived from waste HDPE and Heavy Gas Oil (HGO) via co-pyrolysis. By considering temperature, catalyst quantity, and HDPE amounts as variables, they identified optimal conditions: 550°C temperature, 0.20 g of HDPE, and 0% catalyst, resulting in a substantial 93% yield of the diesel fuel fraction through ANOVA[56]. Statistical analysis methodologies have been employed in research to improve the production of pyrooil. For instance, Wong et al.[57] utilized reaction time, temperature, and the mass ratio of water to polymer as variables in their study on LDPE. Mueanmas[58] investigated LDPE using temperature, heating rate, and residence time as key variables. Wirawan and Farizal [59] examined LDPE, HDPE, and PP, considering temperature, heating rate, and residence time as influential factors in their research. Verma et al., conducted an experimental analysis on ethanol-premium gasoline blends, evaluating engine performance by examining parameters such as BSFC, BP, BTE across various speed settings (2200, 3200, 4200 rpm) and loads (5, 10, 15, 20 kg). Their findings indicated that the brake power (BP) showed improvement up to 4200 rpm with an increase in load [60]

Nileshkumar et al., conducted an inquiry into the impact of the blend ratio of plastic pyrolysis oil derived from HDPE, LDPE, and PP plastics in proportions of 10%, 20%, 30%, and 50% in a diesel engine. Their documentation revealed that there's negligible variation in BMEP among different blends at lower loads. However, at higher loads, the minimum peak pressure occurred with the 50% blend proportion, at the same time the peak pressure gradually increased with the rise in blend proportion from 10 to 30% under high load conditions[61]
Li et al., conducted an experimental analysis involving a spark ignition engine fuelled with acetone-butanol-ethanol and gasoline blends in various ratios. Their findings revealed that the engine's optimal performance, indicated by a BMEP between 485.17 and 524.07 kPa, was

achieved with a 30% blend of gasoline in the mixture[62]. Alawa and Chakma conducted research on the impact of PO (palm oil) blending and compression ratio on diesel engine performance, focusing on BMEP. Their study revealed that the engine achieved higher BTE, lower SFC, and reduced emissions at an optimal BMEP of 4 bar[63]

CONCLUSION:

Keeping in mind to maximize the amount of plastic oil production and utilization to reduce plastic pollution in the environment, this research has been conducted. Virgin HDPE plastic was collected and pyrolyzed up to 450ºC in a fixed be reactor without any catalysts. Throughout the process, only wax was collected. The yield of wax was maximum during 400-425 ºC temperature range. The wax was distilled in a laboratory-scale simple distillation unit. To obtain the gasoline-like hydrocarbon fuel(C_7-C_{12}), the distillation was carried up to 170ºC. To find the optimum level of plastic oil, it was blended with M91 gasoline with as 2%,4%,6%,8% volume ratio. These different blending were assessed in a single-cylinder stationery, four-stroke SI engine to evolute the BMEP production and power development. The experiments were conducted with different speeds and torque as the input variables for each blending. The input and output variables of the engine were documented and displayed in the graphs BMEP vs torque, BMEP Vs Speed, BMEP Vs Power for the different blending ratios and compared with gasoline performance. To adopt the optimum value of BMEP, statistical analysis method was performed. A theoretical experimental model was developed by using Box-Behnken Design methodology with 3 three factors and three level. The relationship between the variables, experimental and predicted values are examined and assessed by the application of the Response Surface Methodology. Analysis of Variance(ANOVA), the common optimized tool, was used to evaluate the optimal operating parameters. It was proved that the designed experiment was statistically fit and the relationship between the input and responses were displayed in the surface diagram. The results of the ANOVA showed that the maximum of 8.7 bar BMEP was used at 3002.37 rpm speed, 12.2701 Nm torque, and 3.58195 blended ratio for the given different input values.

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