International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V72I5P107

Volume 72 Issue 5, 58-65, May 2024
© 2024 Seventh Sense Research Group®

Original Article

Extraction and Optimization of Oil from Post Hospital Waste Plastic through Catalytic Pyrolysis using Central Composite Design (CCD)

S. Arul Selvan[1], K. Kumaravel[2]

[1,2]*Department of Mechanical Engineering, Annamalai University, Tamil Nadu, India.*

[1]*Corresponding Author : sarulselvan74@gmail.com*

Received: 23 January 2024 Revised: 03 April 2024 Accepted: 13 April 2024 Published: 26 May 2024

Abstract *- In this study, waste plastic oil was extracted and optimized from Post-Hospital Waste Plastic (PHWP) through a catalytic pyrolysis process. The Central Composite Design (CCD) of Response Surface Methodology (RSM) through the Design-Expert software was used in this work to optimize the response by varying the input variables pyrolysis process. In this model, the reaction temperature from 300 to 500°C and retention time from 60 to 120 minutes are considered variable factors, and the yield of waste plastic oil is considered an independent response. The ANOVA of the CCD indicated that all the process-independent variables investigated had significant impacts on the sorption capacity of waste plastic oil obtained from PHWP. This work was split into two phases. In phase I, the retention time and reaction temperature were considered as factors, and waste plastic oil as a response. The obtained experimental data showed that the optimized 90-minute retention time and reaction temperature of 450°C resulted in an optimum yield of waste plastic oil. For the second phase of this work, the optimum retention time (90 min) is set as constant and reaction temperature with catalysts quantity as factors. Three catalysts (Zeolite, Alumina and Silica) with different ratios given by the model are used to increase the yield of waste plastic oil. From the CCD analysis, it is found that the catalysts effectively increase the yield of waste plastic oil.*

Keywords - *Waste Plastic Oil, Pyrolysis, Post-Commercial Waste Plastic, Post-Hospital Waste Plastic, Post-Domestic Waste Plastic.*

1. Introduction

Plastic waste is turning into a significant environmental problem, but it may also be a useful resource. Oil can now be extracted from used plastic thanks to recent technological advancements. Pyrolysis is a thermal decomposition method that disassembles plastic into its constituents, including oil, gas, and carbon black [1]. From gasoline and lubricants through petrochemical feedstock, the oil extracted from waste plastic can be utilized for a number of things. Using leftover plastic in this manner reduces the quantity of plastic that ends up in landfills and is environmentally good [2,3]. Also, it gives businesses that collect and process waste plastic a new source of income. In general, the environment and human health benefit from the oil extraction from waste plastic. By using the method of transforming waste plastic oil into a profitable fuel source, the amount of plastic trash may be lowered, and a new, sustainable source of energy can be created [4-6]. The conversion procedure entails melting and heating plastic garbage in order to extract the oil inside. Before being used as an alternative fuel source, the oil is then cleaned and filtered to remove any contaminants. Waste plastic oil can be converted into an effective and affordable energy source that can be used to run motors or heat homes. The conversion process is quite straightforward [7]. This not only lessens the quantity of plastic waste in the environment but it also provides a renewable energy source that can aid in lowering emissions. A thermoplastic polymer produced from the monomer ethylene is called polyethene (PE). Polypropylene is a very adaptable material and is used in a wide range of products, including toys, packaging, textiles, computer equipment, and pipes. It is also utilized in plastic parts and accessories for vehicles. PE is a versatile polymer that is lightweight, inexpensive, and resistant to most chemicals, moisture, and weathering. Low-density, linear, low-density and high-density PE can all be produced in an assortment of densities and morphologies [8-10]. Low-Density Polyethylene (LDPE), a flexible and adaptable form of plastic manufactured from ethylene, is commonly used. It is employed in various ways, including food storage and packaging. Due to its inexpensive price and lightweight nature, it is frequently used for food packaging. A form of plastic manufactured from ethylene called HDPE (High-Density Polyethylene) is more robust and durable than LDPE. Milk jugs, detergent bottles, and plastic bags are just a few items that frequently use HDPE.

In addition to being more robust and chemical resistant, it is more expensive than LDPE. A thermoplastic polymer with numerous applications is polypropylene (PP) [11-14]. It is renowned for its affordability, simplicity of manufacture, chemical resistance, strength, rigidity, and affordability. Polypropylene is a great material for uses, including packaging, textiles, automotive parts, and medical supplies because of its strong resistance to both high and low temperatures. Injection moulding, blow moulding, and extrusion techniques all frequently employ it.

A popular experimental design technique called Central Composite Design (CCD) tries to predict and optimise responses by repeatedly changing the input variables. It is especially helpful when there is a complicated and nonlinear relationship between the input components and the answer. Software for the Design of Experiments (DOE), like Design-Expert, offers a strong framework for CCD implementation and the extraction of valuable insights from experimental data [15]. Beginning with a factorial design, CCD looks at the impact of each factor at two levels (usually low and high). This first design sheds light on linear impacts.

When fitting response models based on data collected from experiments, the Design-Expert programme speeds the implementation of CCD [16]. It offers resources for locating statistically significant variables, interactions, and nonlinear outcomes. For the purpose of visualising response surfaces, the software creates plots such as contour plots, 3D surface plots, and interaction plots. Understanding the connections between many inputs and outcomes is made easier by these images.

The software discovers the ideal factor levels that achieve the user’s optimisation goals, such as maximising or minimising a reaction [17]. The programme provides tools for hypothesis testing, Analysis of Variance (ANOVA), and diagnostics to guarantee the model's validity. Researchers and engineers can effectively investigate complex interactions between causes and responses when using Central Composite Design in conjunction with Design of Experiments tools like Design-Expert. Offering a structured method for testing and analysis, it assists in process optimisation, cuts down on experimental time, and helps with data-driven decisions.

This paper focuses on the extraction and optimization of oil from post-hospital waste plastic via catalytic pyrolysis, employing the Central Composite Design (CCD) methodology. Catalytic pyrolysis offers several advantages over conventional pyrolysis, such as enhanced product yields, improved quality of end products, and reduced environmental impact. By leveraging CCD, a statistical experimental design technique, this study aims to systematically investigate the effects of key process parameters on the yield and quality of oil obtained from post-hospital waste plastic pyrolysis. The significance of this research lies in its potential to address two pressing issues simultaneously: the management of hazardous post-hospital plastic waste and the production of valuable liquid fuels. By optimizing the pyrolysis process using CCD, insights can be gained into the interactions between process variables, catalyst properties, and product characteristics, leading to the development of efficient and sustainable waste-to-energy conversion strategies.Through a comprehensive literature review, this introduction will provide context for the study by discussing the current state of plastic waste management, the principles of catalytic pyrolysis, and the applications of CCD in process optimization. Subsequently, the research objectives, methodology, and expected contributions will be outlined, setting the stage for a detailed investigation into the extraction and optimization of oil from post-hospital waste plastic through catalytic pyrolysis using CCD.

2. Feedstock

Post-hospital waste plastic (PHWP) feedstock has been used to produce three kinds of pyrolysis liquids. After pretreating the waste plastic they undergo shredding in flakes having a size of 50 mm to make a granulated material. Then, PHWP granules come from hospital waste from the primary sorting process, in which bulky materials are manually separated in a closed booth. The polymer composition of the post-hospital plastic waste is 78% of LDPE.

3. Reactor Setup

The Post-Hospital Waste Plastic (PHWP) was chosen as the source because it accounts for a sizable portion of the waste plastic generated. Silica, alumina, zeolite, and their mixtures were discovered as catalysts for the investigation. Between 300 and 500 °C is the reaction temperature. Using nitrogen as a carrier gas before turning on the electric heater creates the inert atmosphere needed for pyrolysis. These decisions about the polymer-to-catalyst ratio and reaction temperature ranges were based on the results of the literature review that was conducted. Figure 1 illustrates the pyrolysis setup schematically.The setup includes an electric heater, a reactor, a condenser, a temperature controller, a K-type thermocouple, a pressure gauge, a water pump, an oil collector, and a nitrogen source (inert gas). Three kilograms of used plastic could be loaded into the reactor at once. The reactor comprises a 1500 W electric heater placed beneath the reactor configuration.

The condenser was a counter-flow heat exchanger with dimensions of 25 cm in length and 26 cm in diameter. The coolant is water that has been cooled down to about 20°C. A steel container with dimensions of 15 cm in diameter and 20 cm in height is filled with waste plastic. Finally, this container is positioned above the electric heater. A manhole was built into the reactor's bottom to allow for the removal of the converted sludge. The reactor's top has a safety valve installed for protection. The weights of the catalyst and the polymers are measured using a portable weighing scale.

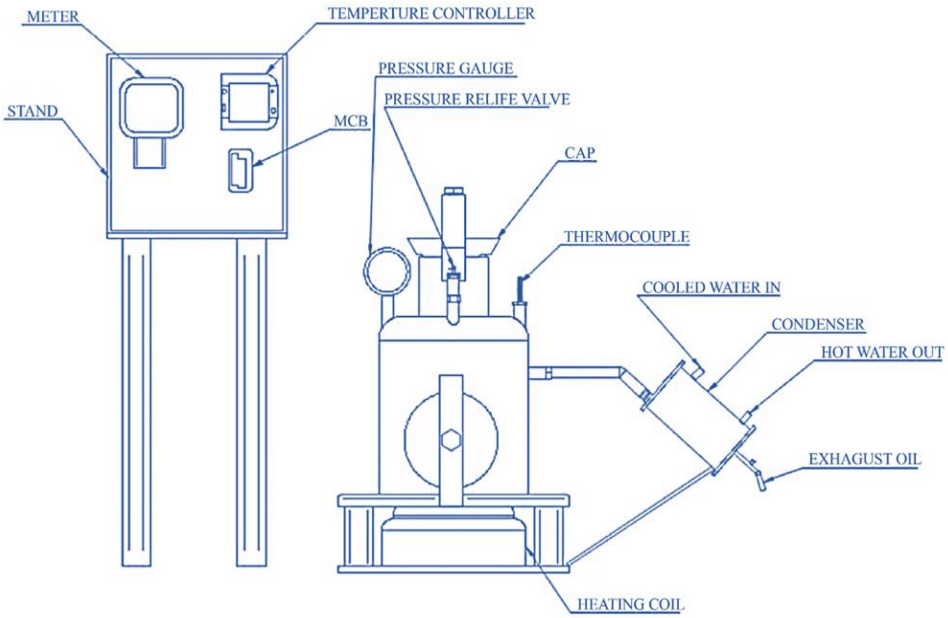

Fig. 1 Pyrolysis setup

Before being delivered to the reactor, the catalyst and waste plastic were appropriately combined. Because of the reactor's vertical configuration, nitrogen gas was injected into it through a manhole. By replacing the air in the reactor with nitrogen, the pyrolysis reaction can occur in an anaerobic environment.

This work employed a temperature controller to maintain the reactor's temperature. The temperature controller is wired up to the heating coil's power supply. At the reactor's top, a K-type thermocouple was installed to measure the temperature, and its other end was wired to a temperature controller. If the input temperature is attained, the temperature controller turns off the electricity to the heating coil and keeps the reactor at the set temperature. At the top of the reactor is a pressure gauge that measures the pressure. To determine the amount of power used in this configuration, a power meter is installed. Prior to beginning the heating process, nitrogen gas is permitted to pass through the heater unit to eliminate any initial oxygen present. The heater is turned on, after which the temperature controller is set to the necessary operating temperature. In the condenser, the gas mixture is cooled. Water delivered to the condenser for cooling purposes is 10°C in temperature. By adding ice cubes to a water bucket, a low temperature for the water is created. A small portion of the uncondensed part that is still present escapes into the atmosphere.

4. Analytical Methods

An analysis of variance (ANOVA) for a quadratic response surface model is a statistical method for determining the importance of various variables and their interactions in a quadratic regression model that depicts the relationship between a response variable and numerous predictor variables. A quadratic model, employed in the response surface technique, is a mathematical depiction of the relationship between the response variable (such as product yield, temperature, or quality) and the predictor variables (factors or inputs) that may affect it. The quadratic model has linear, quadratic, and even cross-product elements to account for both linear and nonlinear effects in addition to interactions between variables. ANOVA is a statistical method for dividing the entire variation in the response variable into distinct components containing the main effects of variables and interactions.

In a Response Surface Quadratic Model, ANOVA aids in finding the variables and interactions that statistically significantly contribute to the variability of the response variable. Analysis of variance (ANOVA) for the response surface quadratic model of waste plastic oil from PHWP is given in Table 1.The Model F-value of 149.35 implies that the model is significant. There is only a 0.01% chance that a "Model F-value" this large could occur due to noise.

Values of "Prob > F" less than 0.0500 indicate that model terms are significant. In this case, A, B, A^2, B^2 are significant model terms. Values greater than 0.1000 indicate that the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Lack of Fit F-value" of 19.42 implies that the Lack of Fit is significant. There is only a 0.76% chance that a "Lack of Fit F-value" this large could occur due to noise. Figure 2 shows the Normal % probability plot of residuals of waste plastic oil from PHWP.

Table 1. Analysis of variance (ANOVA) for response surface quadratic model of waste plastic oil from PHWP

Source Model	Sum of Squares	DF	Mean Square	F Value	Prob>F	
Model	2.159E+005	5	43181.38	149.35	< 0.0001	Significant
A	11475.36	1	11475.36	39.69	0.0004	
B	1.861E+005	1	1.861E+005	643.69	< 0.0001	
A^2	5850.43	1	5850.43	20.24	0.0028	
B^2	14243.91	1	14243.91	49.27	0.0002	
AB	306.25	1	306.25	1.06	0.3376	
Residual	2023.85	7	289.12			
Lack of Fit	1893.85	3	631.28	19.42	0.0076	Significant
Pure Error	130.00	4	32.50			
Cor Total	2.179E+005	12				

The CCD ANOVA model can be represented in the following general form:

$Y = \beta0 + \beta1X1 + \beta2X2 + \beta3X1^{\wedge}2 + \beta4X2^{\wedge}2 + \beta5X1X2 + \varepsilon$

Where:

- Y represents the response variable (waste plastic oil yield).
- X1 and X2 are the coded levels of the two factors under investigation (catalyst concentration and reaction temperature, for example).

- β0 is the model intercept.
- β1, β2, β3, β4, and β5 are the coefficients of the model, representing the main effects and interaction effects.
- ε is the error term, representing the random variability in the data. Figure 3 shows the Response surface model with the response variable of waste plastic oil yield from PHWP. The yield of waste plastic oil depends on both retention time and reaction temperature. When the reaction temperature increases in the pyrolysis reactor, the yield of waste plastic oil from both PHWP was found to increase.

The optimum reaction temperature was found as 450-480°C. Similarly, the retention time also plays a vital role in the yield of waste plastic oil. Adequate retention time permits the completion of desired chemical reactions while minimizing the formation of unwanted derivatives, such as char or gases [18].

When the retention time increases, it gives more time to degrade the plastic and provide a higher amount of yield. In both cases, 90 – 100 minutes of retention time was found as optimum to get a higher yield of waste plastic oil. Response surface model of waste plastic oil yield from PHWP with Zeolite, Al_2O_3 and SiO_2 catalysts at different ratios were shown in Figures 4 to 12.

Response surface Model of waste plastic oil yield from PHWP with Zeolite + 5% Al_2O_3 + 5% SiO_2 catalysts Al_2O_3 and SiO_2 catalysts also effectively increase the oil yield from PHWP. Alumina and silica are thermally stable substances that can endure high temperatures include. These catalysts either offer other catalytic components a solid support structure or aid in maintaining the integrity of the reaction vessel in pyrolysis, where high temperatures are employed to break down feedstock materials [19].

Depending on their chemical characteristics and the circumstances of their use, alumina and silica catalysts can function as Lewis or Brnsted acid or base sites.

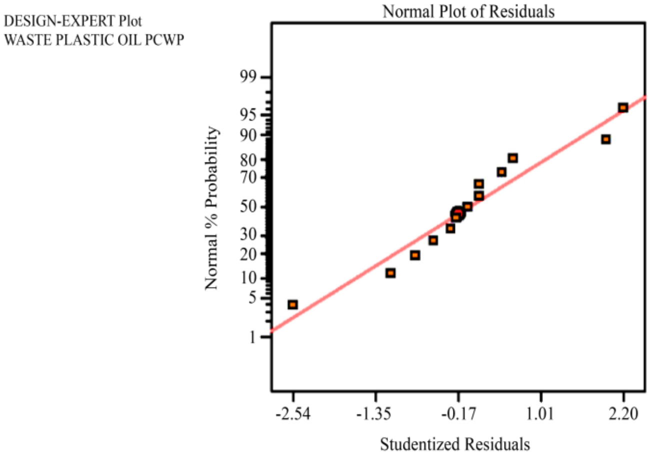

Fig. 2 Normal % probability plot of residuals of waste plastic oil from PHWP

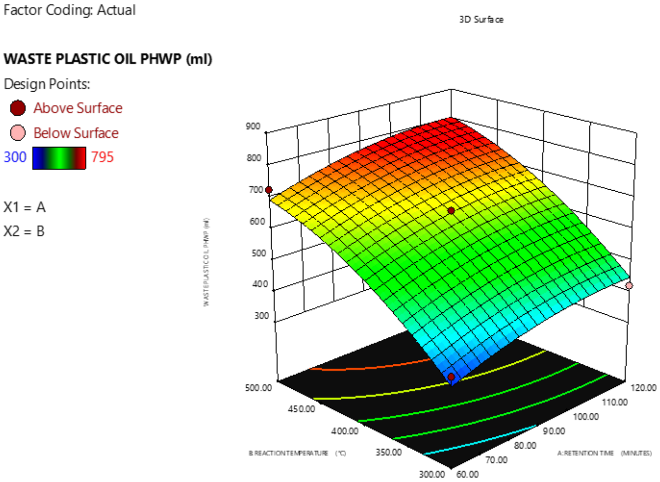

Fig. 3 Response surface Model of waste plastic oil yield from PHWP

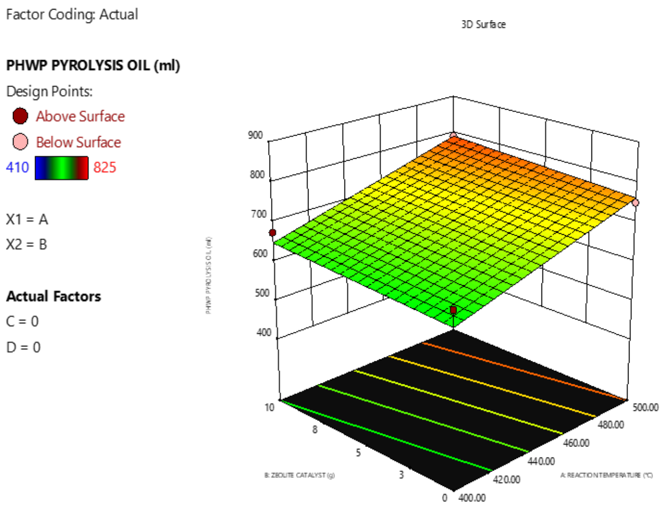

Fig. 4 Response surface Model of waste plastic oil yield from PHWP with Zeolite + 0% Al_2O_3 + 0% SiO_2 catalysts

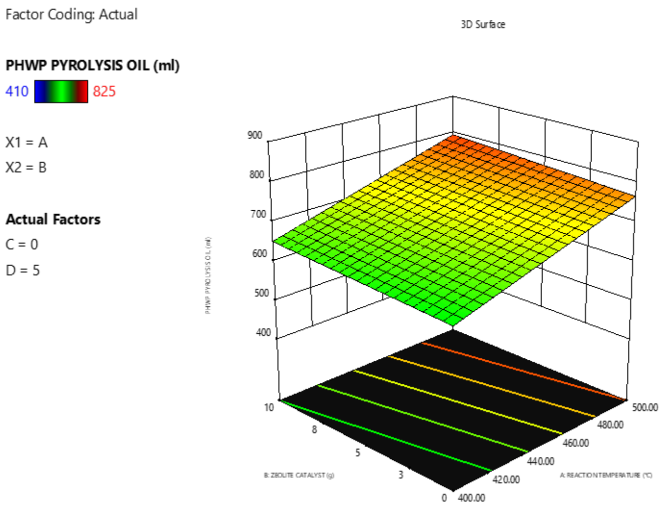

Fig. 7 Response surface Model of waste plastic oil yield from PHWP with Zeolite + 0% Al_2O_3 + 5% SiO_2 catalysts

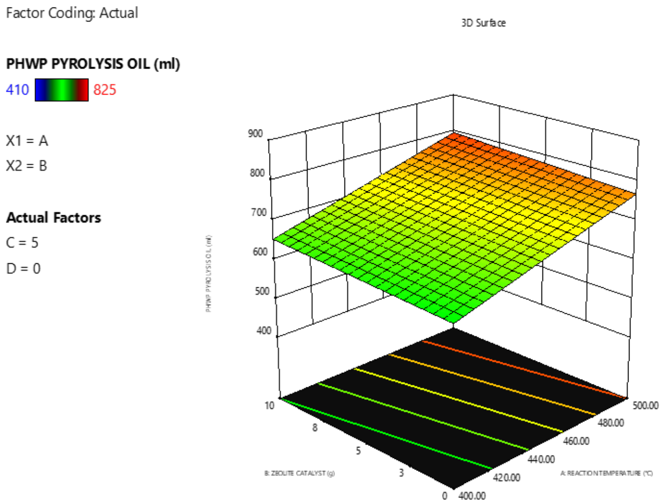

Fig. 5 Response surface Model of waste plastic oil yield from PHWP with Zeolite + 5% Al_2O_3 + 0% SiO_2 catalysts

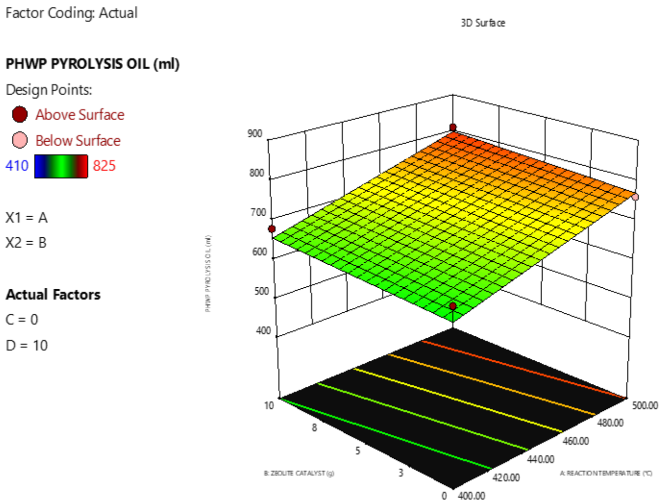

Fig. 8 Response surface Model of waste plastic oil yield from PHWP with Zeolite + 0% Al_2O_3 + 10% SiO_2 catalysts

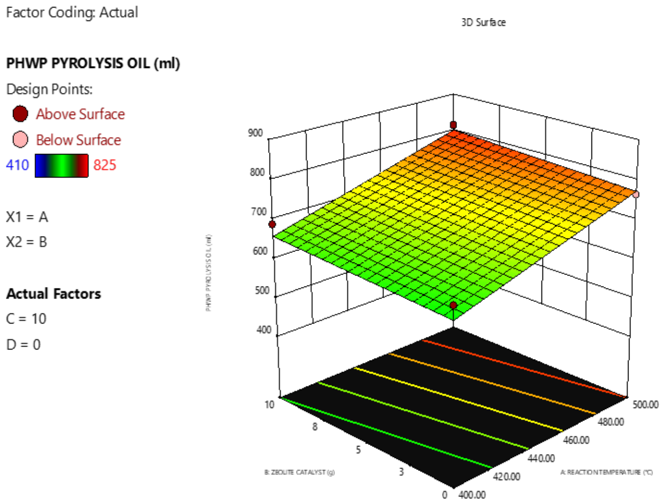

Fig. 6 Response surface Model of waste plastic oil yield from PHWP with Zeolite + 10% Al_2O_3 + 0% SiO_2 catalysts

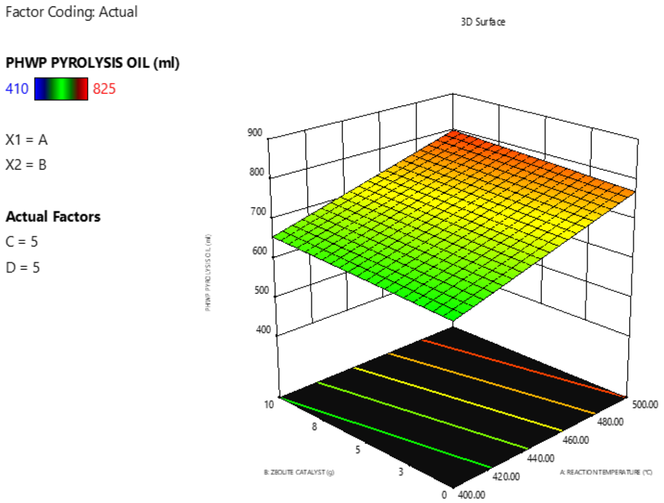

Fig. 9 Response surface Model of waste plastic oil yield from PHWP with Zeolite + 5% Al_2O_3 + 5% SiO_2 catalysts

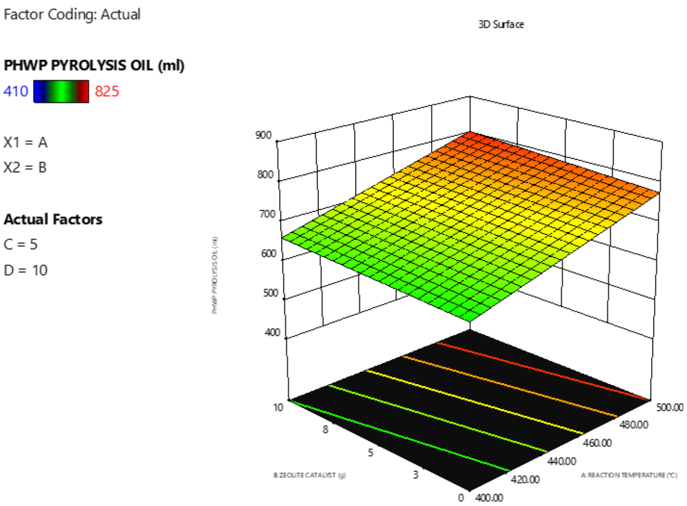

Fig. 10 Response surface Model of waste plastic oil yield from PHWP with Zeolite + 5% Al_2O_3 + 10% SiO_2 catalysts

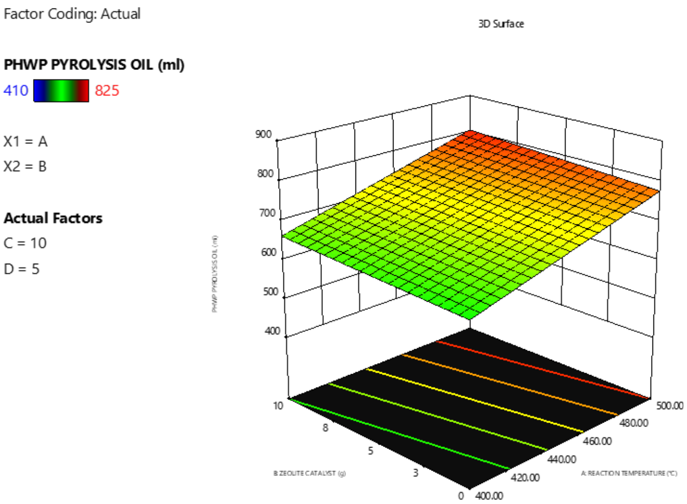

Fig. 11 Response surface Model of waste plastic oil yield from PHWP with Zeolite + 10% Al_2O_3 + 5% SiO_2 catalysts

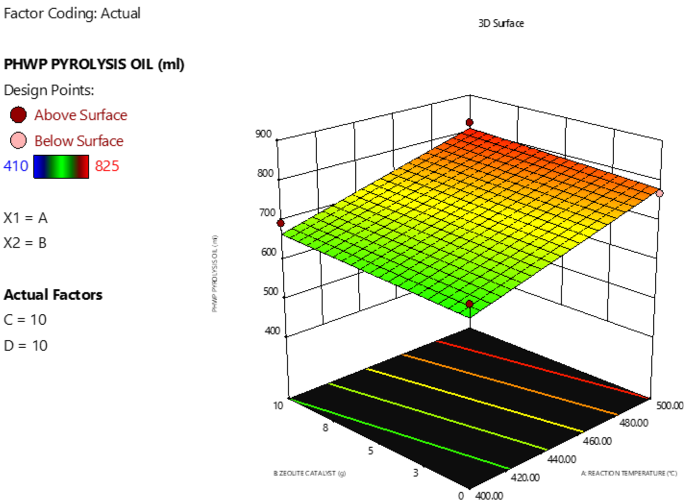

Fig. 12 Response surface Model of waste plastic oil yield from PHWP with Zeolite + 10% Al_2O_3 + 10% SiO_2 catalysts

Table 2. Thermo-Physical Properties of extracted PHWP oil

Parameter Name	Unit	Diesel [15]	PHWP oil
Flashpoint by PMCC method	°C	38	32
Fire point by PMCC method	°C	48	44
Calculated cetene index	-	53.90	51.01
Gross calorific value	kcal/kg	10371	10124
Viscosity @ 40°C	cSt	2.29	2.11
Density @ 15°C	g/ml	0.8390	0.8354

They can catalyze a variety of acid- or base-catalyzed processes in pyrolysis that might take place during the breakdown of feedstock materials. With the aid of these catalytic sites, complex organic compounds can be broken down into simpler hydrocarbons through processes including cracking, dehydration, and isomerization [20]. The yield of waste plastic oil was found to be higher in the case of a combination of these three catalysts simultaneously. Al_2O_3 and SiO_2 catalyst increases the yield up to 30 to 50 ml when increasing the ratio from 5 to 10 percent.

5. Analysis of the Properties of PHWP Oil

The flash point of a substance is the lowest temperature at which it can vaporize to form an ignitable mixture in the air. It is the temperature at which a material can catch fire momentarily if exposed to an open flame or spark. The fire point is the temperature at which a substance will continue to burn after being ignited. It is higher than the flash point and represents the point at which sustained combustion occurs. In the case of PHWP oil, both fire and flash points were found to be lower than that of diesel fuel.

At the same time, fire and flash points were 32 and 44°C, respectively, for PHWP oil. The cetane index is a useful tool for estimating the ignition quality of waste plastic oil and other alternative fuels without conducting the full cetane number laboratory test. The calculated cetene index of the PHWP oil was found to be 53.90, which is nearer to the diesel value (calculated cetene index of Diesel – 51.01[15]). It is important to note that waste plastic oil has a Gross calorific value (GCV) lower than that of traditional fossil diesel fuel.

However, the GCV of waste plastic oil is still significant, making it a potential source of energy. The GCV value of PHWP oil was found to be 10124 Kcals/Kg. The viscosity of PHWP oil can vary widely based on the specific composition of the feedstock and the pyrolysis conditions. Viscosity measurements are conducted at various temperatures, as viscosity is temperature-dependent. The viscosity of waste plastic oil can be slightly lower than that of traditional diesel fuel. The Viscosity of PHWP oil at 40°C was 2.11cst, whereas it was 2.29cst for diesel fuel. The density of PHWP oil is measured using the Pycnometer Method. The density of PHWP oil refers to the mass per unit volume of the oil derived from the conversion of waste plastic.

From the results, it is clear that the density of PHWP oil was found to be slightly lower than that of diesel fuel. The density of PHWP oil was 0.8354Gm/ml, whereas it was 0.8390Gm/ml for neat Diesel.

6. Conclusion

The utilization of CCD for optimization brings precision and efficiency to the process, allowing for the fine-tuning of various parameters involved in waste plastic oil production. This optimization can lead to increased yields and improved quality, making the entire process more economically viable and environmentally friendly.

However, it is important to acknowledge that the implementation of waste plastic oil production from hospital waste with CCD optimization may face certain challenges, such as regulatory and safety considerations, as well as the need for specialized equipment and skilled personnel.

Nonetheless, with proper planning, research, and collaboration between the healthcare sector and the recycling industry, these challenges can be overcome.
It is concluded from the results;

- The yield of 795ml of oil was obtained from the one Kg of post-hospital waste plastics through the pyrolysis process.
- The yield of waste plastic oil was further increased by using catalysts like Zeolite, Alumina, and Silica.
- The maximum yield of 825ml was found in the case of a combination of these three catalysts, each at a ratio of 10%.

References

[1] Guangcan Su et al., "Valorisation of Medical Waste through Pyrolysis for a Cleaner Environment: Progress and Challenges," *Environmental Pollution*, vol. 279, pp. 1-13, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[2] Luis Alberto De la Flor-Barriga, and Ursula Fabiola Rodríguez-Zúñiga, "Numerical Analysis on a Catalytic Pyrolysis Reactor Design for Plastic Waste Upcycling Using CFD Modelling," *RSC Advances*, no. 12, pp. 12436-12445, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[3] Uisung Lee, J.N. Chung, and Herbert A. Ingley, "High-Temperature Steam Gasification of Municipal Solid Waste, Rubber, Plastic and Wood," *Energy and Fuels*, vol. 28, no. 7, pp. 4573-4587, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[4] Rohit Kumar Singh et al., "Impact of Fast and Slow Pyrolysis on the Degradation of Mixed Plastic Waste: Product Yield Analysis and their Characterization," *Journal of the Energy Institute*, vol. 92, no. 6, pp. 1647-1657, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[5] M. Mani, C. Subash, and G. Nagarajan, "Performance, Emission and Combustion Characteristics of a DI Diesel Engine Using Waste Plastic Oil," *Applied Thermal Engineering*, vol. 29, no. 13, pp. 2738-2744, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[6] Ioannis Kalargaris, Guohong Tian, and Sai Gu, "Combustion, Performance and Emission Analysis of a DI Diesel Engine Using Plastic Pyrolysis Oil," *Fuel Processing Technology*, vol. 157, pp. 108-115, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[7] Mateo Cordier et al., "Plastic Pollution and Economic Growth: The Influence of Corruption and Lack of Education," *Ecological Economics*, vol. 182, pp. 1-13, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[8] Ceyla Güngör et al., "Engine Performance and Emission Characteristics of Plastic Oil Produced from Waste Polyethylene and its Blends with Diesel Fuel," *International Journal of Green Energy*, vol. 12, no. 1, pp. 98-105, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[9] Hariram Venkatesan et al., "Experimental Study on Combustion and Performance Characteristics in a DI CI Engine Fuelled with Blends of Waste Plastic Oil," *Alexandria Engineering Journal*, vol. 57, no. 4, pp. 2257-2263, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[10] V.L. Mangesh et al., "Combustion and Emission Analysis of Hydrogenated Waste Polypropylene Pyrolysis Oil Blended with Diesel," *Journal of Hazardous Materials*, vol. 386, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[11] Amar Kumar Das et al., "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, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[12] Sudershan B. Gadwal et al., "Performance and Emission Characteristic Studies on CRDI Diesel Engine Fuelled with Plastic Pyrolysis Oil Blended with Ethanol and Diesel," *International Journal of Sustainable Engineering*, vol. 12, no. 4, pp. 262-271, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[13] Maridu Bhargavi et al., "Effective Utilization and Optimization of Waste Plastic Oil with Ethanol Additive in Diesel Engine Using Full Factorial Design," *Materials Today: Proceedings*, vol. 52, pp. 930-936, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[14] Khatha Wathakit et al., "Characterization and Impact of Waste Plastic Oil in a Variable Compression Ratio Diesel Engine," *Energies*, vol. 14, no. 8, pp. 1-18, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[15] C. Syed Aalam, and C.G. Saravanan, "Effects of Fuel Injection Pressure on CRDI Diesel Engine Performance and Emissions Using CCD," *International Research Journal of Engineering and Technology*, vol. 2, no. 5, pp. 1411-1416, 2015. [Google Scholar] [Publisher Link]

[16] Natthawat Thonglhueng et al., "Optimization of Iodine Number of Carbon Black Obtained from Waste Tire Pyrolysis Plant via Response Surface Methodology," *Heliyons*, vol. 8, no. 12, pp. 1-10, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[17] Jonghun Lim et al., "Optimal Strategy to Sort Plastic Waste Considering Economic Feasibility to Increase Recycling Efficiency," *Process Safety and Environmental Protection*, vol. 165, pp. 420-430, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[18] C. Syed Aalam, and C.G. Saravanan, “Effects of Nano Metal Oxide Blended Mahua Biodiesel on CRDI Diesel Engine,” *Ain Shams Engineering Journal*, vol. 8, no. 4, pp. 689-696, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[19] C. Syed Aalam, C.G. Saravanan, and M. Kannan, “Experimental Investigations on a CRDI System Assisted Diesel Engine Fuelled with Aluminium Oxide Nanoparticles Blended Biodiesel,” *Alexandria Engineering Journal*, vol. 54, no. 3, pp. 351-358, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[20] C. Syed Aalam, C.G. Saravanan, and B. Prem Anand, “Impact of High Fuel Injection Pressure on the Characteristics of CRDI Diesel Engine Powered by Mahua Methyl Ester Blend,” *Applied Thermal Engineering*, vol. 106, pp. 702-711, 2016. [CrossRef] [Google Scholar] [Publisher Link]