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Improvement of Volumetric Flow Rate of Biodiesel Oil from Waste Plastics Pyrolysis Plant for Biodiesel Recovery using Response Surface Methodology.

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Abstract

The present study deals with the effect of input (independable) variables: reactor inlet temperature, production time, inlet pressure, and heating rate on the dependable variables: volumetric flowrate, and product yield from the waste plastic pyrolysis plant as well as their optimization. The experiment was designed with Central composite design (CCD) at a time of production of 43 – 60 minutes, an inlet temperature of 310 – 500^{0}C, an inlet pressure of 2 – 2.5 bar and a heating rate of 5 - 50^{0}C/min. The result showed a product yield of 87.3% and a volumetric flow rate of 1.17 m^3/s at the production time of 54 minutes, 360^{0}C inlet temperature, 2.35 bar inlet pressure, and 20 min/C heating rate. From the optimization study, the operating parameters that affected the increase in volumetric flow rate and product yield were reactor inlet temperature, production time, inlet pressure, and heating rate. Increasing the reactor inlet temperature, pressure, heating rate, and time of production results increase in the yield of petroleum products from the waste plastics pyrolysis plant and the volumetric rate. The optimal values of the results were: the inlet temperature to the reactor, inlet pressure, heating rate, and production time were 379.278^{0}C, 2.419 bar, 58.375 minutes, and 23.363 min./^{o}C, respectively. The product yield and the volumetric flow rate were 83.580% and 0.966 lit./hr, respectively. The input capacity to the waste plastics pyrolysis plant was discovered to be 2kg/hr of thermoplastics. The diesel range hydrocarbons obtained from the plant were C_{10}-C_{13}.

1. Introduction

The generation rate of plastic waste has become a critical concern globally due to the potential threats they pose to the environment [1]. As of 2016, plastic wastes constitute 12% of the global municipal solid waste generation [2] and 11% of Nigeria's total solid waste generation [3]. Lebreton and Andrady (2019) [4] predicted a disproportionately high plastic waste load in Africa in the future years if the developing economies do not significantly invest in waste management infrastructures to reduce the fraction of plastic waste in municipal solid waste. Methods of plastic waste management vary from country to country[5].

Plastic recycling, however, has suffered a setback due to challenges of poor demand for recycled plastic granulate by processors, lack of necessary infrastructures, collection cost, incompatibility of plastics in recycle stream, a low weight-to-volume ratio of films and plastic bags, and the difficulty involved in handling simultaneously flexible and rigid plastic packaging [5].

In Nigeria, the frequently practised waste disposal methods are open dumping, open-air burning, and waste burial, which are unsatisfactory and unfavorable to public health [6]. Therefore, there is a need to engage in more environmentally friendly technology that significantly reduces plastic waste and recovers high-calorific fuels from plastic waste mixtures. Pyrolysis, a thermochemical conversion method, has gained the attention of researchers as an environmentally friendly technology for converting solid wastes and biomass[7]. It is a thermal decomposition of solids, usually at a typical temperature range of 300°C–600°C in the absence of oxygen, to yield pyrolytic oil, char, and non-condensable gas[8]. The pyrolysis fuel produced is known to have comparable properties and composition to petroleum-derived fuels, and its combustion does not emit hazardous and greenhouse gases. [9-11] produced sweet-smelling hydrocarbon naphtha compounds by thermal degradation of polystyrene (PS) waste plastic. Polystyrene (PS) waste plastic to sustainable power or naphtha-grade fuel production through fragmentary refining. The PS liquefaction range was 250 - 430°C, and the incomplete segment temperature was 110 - 135°C for the naphtha-grade fuel division. For test reasons, the crude sample was 1 kg of PS waste plastic.

Fakhrhoseini, S. M. and Dastanian, M. (2013) [12] researched thermal recycling of solid tire wastes for alternative liquid fuel: the first commercial step in Bangladesh. They designed a plant with two pyrolysis units, each consisting of a horizontal axis rotary type batch mode reactor with a recycling capacity of 4.5 tons/run, as seen in Fig. 2.12. Solid tire wastes in half/full size were fed into the reactor chamber, operating at 420°C with a light over-pressure of 0.03 bar. The reactor was heated externally by burning product pyrolysis liquids for the first three hours and by burning product pyro-gas for five hours. The products distribution from their plant operating at optimum condition were found as; oil 45 wt%, char 35 wt% and gases 10 wt%, and steel cords 10 wt% of solid tire waste. The product fluids have been found to have a high gross calorific worth (GCV) of around 44 MJ/kg, which would support their utilization as swaps for conventional fluid fuels. Moreover, pyrolytic burns might be utilized as a solid fuel, initiated carbon, printer ink, etc. Pyrolysis gas contains high concentrations of methane, ethane, and butadiene.

Arabiourrutia, M., *et al.* (2017) [13] worked on Waste truck-tire processing by flash pyrolysis in a conical spouted bed reactor in Fig.2.13. They studied the continuous pyrolysis of waste truck tires in a bench-scale plant with a conical spouted bed reactor in the 425–575˚C range. A temperature of 475˚C was required to devolatilize waste tire rubber completely; the char produced at 425˚C contained a significant amount of volatile matter—the maximum TPO yield of 58 wt. % was obtained between 425 and 475˚C. In addition, the highest limonene production of 14.1 wt. % was obtained at 475˚C, which remarked the interest of this pyrolysis temperature. A further temperature increase to 575˚C increased the gas yield to the detriment of TPO, whose yield was decreased to 54 wt.%, just as that of limonene to 7.1 wt.%. Additionally, the TPO goes through a momentous aromatization, i.e., the sweet-smelling content in the TPO is 12.7 wt. % at 475˚C, and this worth was increased to 50.6 wt.% at 575˚C.

Sultan *et al.* (2020)[14] analyzed pyro-oil and wax recovery from reclaimed plastic waste in a continuous auger pyrolysis reactor. This work reported processing reclaimed plastic wastes from an unsanitary landfill site in Kuwait using a bench-scale continuous auger pyrolysis system. First, the plastic feedstock was characterized. After a simple thermal densification process, the material was fed to the pyrolysis system at 500^0C. The pyro-oil and wax products were collected and characterized. The process mass balance was developed dryly, and the yields of pyro-oil, light wax, heavy wax, and gases were 5.5, 23.8, 69.4, and 1.3 wt%, respectively. The findings have indicated that the reclamation of plastic waste from landfills was feasible regarding product distribution and characteristics. Further liquid analysis confirmed that the liquid products contained fractions comparable to petrol and diesel fuels. The wax products are viable and can be applied as a coating, covering and lubricated. Nigeria, like other developing nations, is facing myriads of energy-related problems, including environmental challenges due to the exploration and exploitation of fossil fuel, depletion of fossil fuel reserves, inadequate electricity supply due to rapid population growth, and lack of proper planning by the government [15]. These highlighted challenges in Nigeria and other nations could be resolved by utilizing abundant renewable energy resources such as plastics. Pyrolysis is considered the most efficient and promising conversion method with a high fuel-to-feed ratio compared to other thermochemical methods [16]. Municipal plastic wastes are usually heterogeneous, consisting of mixtures of different types of plastics in the dumping area [17]. The quantity and quality of fuel produced via pyrolysis depend on factors such as the composition of the feedstock and process parameters such as residence time and reactor temperature [8,18]. The yield of the liquid fuel from the pyrolysis reaction depends on the relationship of parameters set in the process. In such a situation, optimization will be adopted, which needs to address both the component mixture and process parameters simultaneously [19]. Response Surface Methodology**,** RSM **(**also known as Response Surface Modeling**),** is a technique to optimize the response(s) when two or more quantitative factors are involved. The dependent variables are known as responses, and the independent variables or factors are primarily the predictor variables in response surface methodology. Response surface methodology (RSM) has the advantage of reducing the number of costly experiments by selecting the right experimental conditions. Therefore, response surface methodology (RSM) can be used to solve the optimization problem to maximize the liquid yield. Therefore, the present study seeks to optimize the process parameters for the pyrolysis of waste plastic plant, using Response Surface Methodology (RSM). Different factors, such as feedstock blending ratio, pyrolysis temperature, resident time, heating rate, particle size, feed-to-catalyst ratio, etc., improve pyrolysis oil's yield and quality parameters during pyrolysis.

The optimization of these process parameters is a significant and exciting area currently gaining momentum. RSM is a tool that allows the interaction of reaction parameters on the responses. Thus, optimization of the process parameters can be achieved. Based on this context, the present study seeks to optimize the process parameters for the pyrolysis of waste plastic plant using Response Surface Methodology (RSM).

2. Materials and Method

2.1. Collection of plastic waste

Waste plastics (thermoplastics) materials to be used for the pyrolysis reactions are Polyethylene (PE) (Plastic bottle water, soft drink plastics bottle), Polypropylene (PP) (sachet water, waterproof)

2.2. Description of the pyrolysis plant.

The production method for converting plastics to liquid fuel was based on the pyrolysis of the plastics and the condensation of the resulting hydrocarbons. The plastic waste is first shredded into sizes and removed from any moisture content. The mixture of waste plastics and catalysts (quartz sand and iron) is then introduced into the reactor, enhancing oil vapour degradation from higher molecular weight to lower molecular weight and is called the primary cracking process. The waste plastics were heated and melted at a temperature range of 150-180^{0}C. The melted liquid plastics were decomposed or vaporised at the inlet reactor temperature range of 250^{o}C – 500^{o}C.

The evaporated oil was further subjected to secondary cracking in the catalytic cracker. The evaporated oil vapour was also degraded due to the impact on the catalyst (quartz sand and iron chips) at elevated temperatures. The light oil's pressure and flow rate were reduced in the diffuser chamber to allow the fluid to spend more time in the condenser for condensation. The waste plastics vapour was condensed in the air-cool condenser. The heat from the waste plastics vapour was rejected due to the cooling fan brower. The fan channeled a steady flowing air to the condenser to remove heat from the oil gas. The liquid hydrocarbons were then collected in a storage tank through a receiver tank. Gaseous hydrocarbons such as methane, ethane, propylene, and butanes cannot be condensed and were incinerated in a flare stack.

2.2.1 Pyrolysis experimental procedure

The pilot test of the waste plastic pyrolysis plant in the Michael Okpara University of Agriculture Umudike was carried out using shredded 2 kg of mixed waste plastics (PP, PE and PS), measured in the weighing machine. The empty reactor was also measured in the weighing machine. 2 kg of mixed waste plastics and 1.0 kg of catalyst were fed inside the reactor and weighed in the weighing machine. Thermocouples were fitted at the reactor base to regulate inlet temperature from the 3kW heater placed at the bottom of the reactor. The inlet reactor temperatures used to produce one litre of petroleum products were 310, 360, 400, 460 and 500°C at the residence time of 60, 54, 50, 46 and 43 minutes, respectively. The waste plastics pyrolysis plant was powered electrically to produce five different samples of liquid products, and the oil samples were taken to the Principal Laboratory Technologist at National Root Crops Research Institute Umudike for characterisation. The results from the laboratory revealed that liquid oil with a reactor inlet temperature of 310,360,400 and 460°C has close results with standard diesel oil. However, it stressed that the diesel oil (AGO) with a reactor inlet temperature of 360°C was the best and had the same oil quality as regular diesel oil. The reactor was finally weighed in the weighing machine after the experiment. The mass left (residue) and decomposed masses in the reactor were calculated to determine the product yield of the plant.

2.3. Experimental design and Optimization study

The responses and the corresponding factors were modelled and optimized using the response surface methodology. The RSM was used to determine this study's optimum and experimental design matrix specified according to the central composite design (CCD) method. Four effective parameters (production time, Inlet temperature to the reactor, Inlet pressure to the reactor, and Heating rate of the reactor) were studied, with each parameter being evaluated. Each point was investigated to select the points that produced the most significant volume of pyrolytic liquid. The variables and the experimental domain in this design are specified in Table 1.

Table 1. Experimental design for RSM

Input factors	Unit	Low limit (-1)	High limit (+1)
Time of production (t_{pr})	Minutes (min)	43	60
Inlet temperature to the reactor	Celsius (^0C)	310	500
Inlet pressure to the reactor	bar	2	2.5
The heating rate of the reactor	^0C/min	5	50

Three-dimensional response surfaces and contour plots were used to facilitate a straightforward examination of the influence of experimental variables on the responses. The coefficients of the models for one response will be estimated with multiple regression analysis. The fit quality of the models will be judged from their coefficients of correlation and determination. The adequacy of each model will also be checked with the analysis of variance (ANOVA) using Fisher F-test. This test is purposed to determine the relationship between the response variable and a subset of the independent variables.

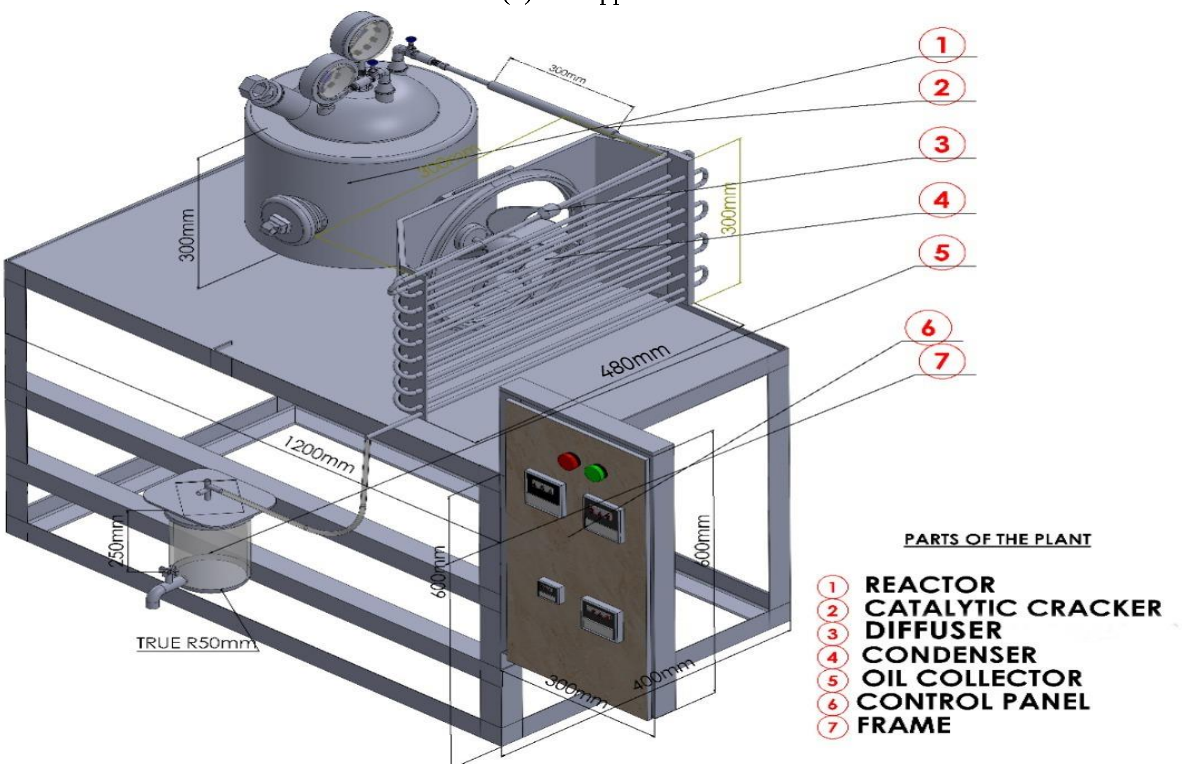

Figure 1: The 3-Dsolid view of the Local waste plastics plant.

Figure 2: The Local waste plastics pyrolysis plant

3. Results and Discussion

3.1. Pyrolysis of the waste plastics material to liquid fuel (Biodiesel).

The pyrolysis results of the waste plastic material designed with Response Surface Methodology (RSM) are presented in Table 2. The independent factors, time of production, Inlet temperature to the reactor, Inlet pressure to the reactor, and Heating rate of the reactor were used in determining the dependent factors of product yield (Py) and volumetric flow rate (Q). The results showed that 87.3% and 1.17 m^3/s are the maximum values of product yield and volumetric flow rate values, respectively, were obtained at the time of production of 54 minutes, 360^0C inlet temperature, 2.35bar inlet pressure, and 20 min./C heating rate.

Table 2. Experimental design result for the pyrolysis of waste plastics

Run	Time of production (t_{pr}) (min)	Inlet temperature to the reactor (C)	Inlet pressure to the reactor (bar)	The heating rate of the reactor (min)	Product yield	Volumetric flow rate (Q)
1	60	310	2.2	5	84.25	1.08
2	58	320	2.25	10	84.25	1.08
3	56	340	2.3	15	84.25	1.08
4	54	360	2.35	20	87.3	1.17
5	52	380	2.38	25	84.25	1.089
6	50	400	2.4	30	84.25	1.091
7	48	420	2.42	35	84.25	1.091
8	46	460	2.44	40	82	0.9569
9	44	480	2.47	45	82	0.9517
10	43	500	2.5	50	82	0.9504

3.3. Analysis of variance (ANOVA) results for the pyrolysis of waste plastic

The statistical analysis for the pyrolysis of the waste plastic into liquid fuel was done using Analysis of Variance (ANOVA). Tables 2 and 3 showed the ANOVA results of the product yield and volumetric flow rate (Q), respectively. The multiple regression analysis for the pyrolysis of the plastic waste materials indicated a linear model, as shown in equation (1).

$$Py = 122.14218 + 0.043890 \times A - 0.096733 \times B - 5.91097 \times C + 0.422290D \qquad (1)$$

The interaction effects of the time of production (A), Inlet temperature to the reactor (B), Inlet pressure to the reactor (C), and Heating rate of the reactor (D) were studied using the contour plot and 3D surface plot of RSM depicted in figures 1and 2. The graph showed that an increase in the production time increases the product yield, while an increase in the inlet temperature of the reactor increases the product yield too.

Table 3. ANOVA results for Product Yield

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	10.3	4	2.57	32.07	0.0009	significant
A-tpr	0.0012	1	0.0012	0.0145	0.9088	
B-T1	1.63	1	1.63	20.35	0.0063	

C-P1	0.0358	1	0.0358	0.4458	0.5339
D-he	0.3764	1	0.3764	4.69	0.0827
Residual	0.4015	5	0.0803		
Cor Total	10.7	9			
Std. Dev.	0.2834		**R^2**	0.9625	
Mean	83.58		**Adjusted R^2**	0.9325	
C.V. %	0.339		**Predicted R^2**	NA	
			Adeq Precision	13.2576	

It can be deduced from the F-value of 32.07 in Table 3 with a correspondingly low probability value of 0.0009, which is less than 0.05, that the model terms are significant. In this case, the adequate precision value (P adeq = 13.2576) is greater than 4, which is desirable for the model showing an adequate signal-to-noise ratio of the model.

Table 3 shows a standard deviation of 0.2834, mean of 83.58, C.V. of 0.339, R^2 of 0.9625, adj. R^2 of 0.9325 and adequate precision of 13.2576 were obtained for the product yield. The fitness of the linear model was expressed by the coefficient of determination of R^2 and the coefficient of adjusted R^2, which were obtained as 0.9625 and 0.9325, respectively. It is suggested that these values should be at least 0.80 for the excellent fit of the model (Goos & Gilmour, 2013). Therefore, the R^2 and adjusted R2 values indicated that the regression model is acceptable.

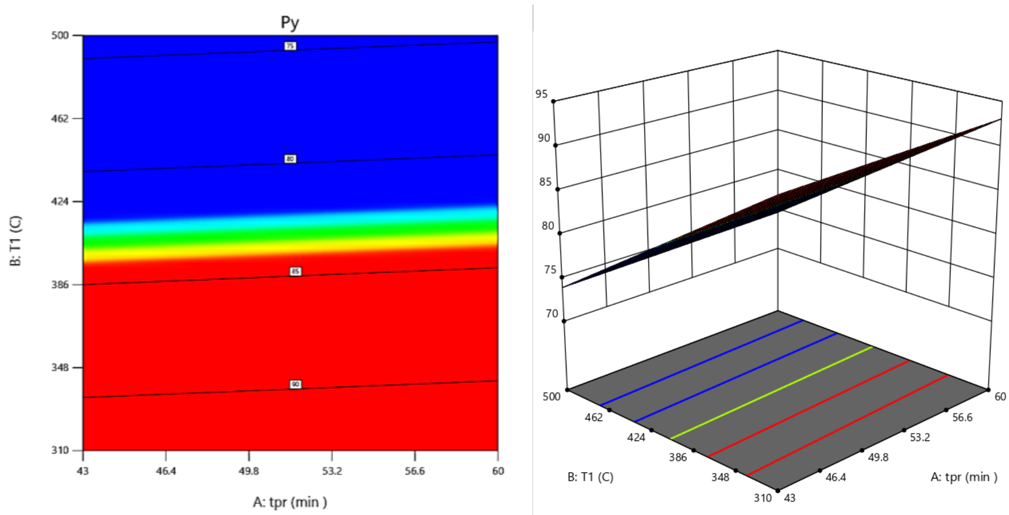

Figure 3: Contour and a 3D plot showing the effects of time of production and inlet temperature on the reactor on product yield (Py)

The multiple regression analysis for the pyrolysis of the plastic waste materials indicated a linear model for the volumetric flow rate (Q), as shown in equation (2).

$$Q = 4.77426 - 0.006943A - 0.006407B - 0.657535C + 0.026440D \quad (2)$$

The interaction effects of the time of production (A), Inlet temperature to the reactor (B), Inlet pressure to the reactor (C), and Heating rate of the reactor (D) were studied using the contour plot and 3D surface plot of RSM depicted in figure 4.2 showed that increase in the time of production (tpr) result to simultaneous increase in the volumetric flow rate (Q). Also, an increase in the reactor's inlet temperature increases the liquid fuel's volumetric flow rate.

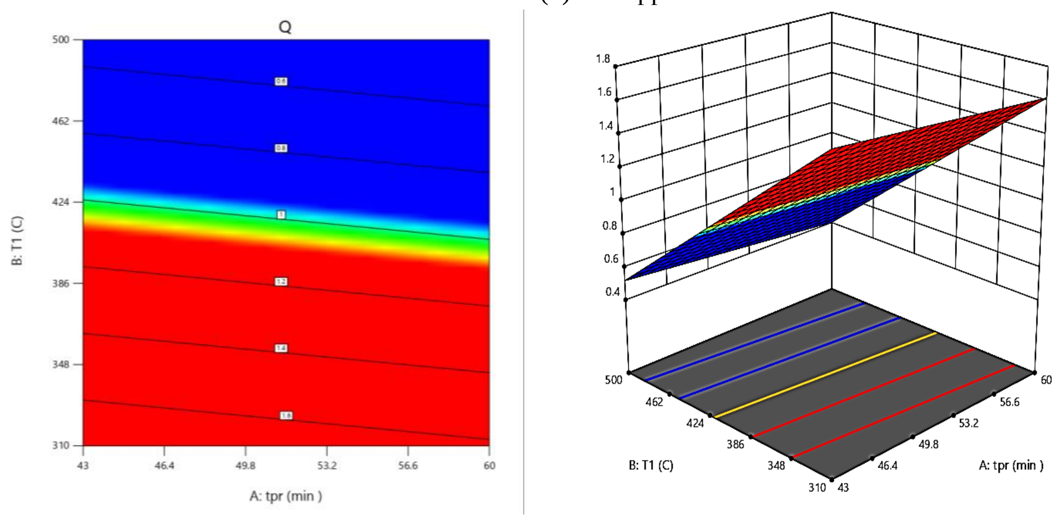

Figure 4: Contour and a 3D plot showing the effects of time of production and inlet temperature to the reactor on the volumetric flow rate (Q)

Table 3 showed a standard deviation of 0. 0192, mean of 1.04, C.V. of 1.84, R^2 of 0.9487, adj. R^2 of 0.9077 and adequate precision of 11.4931 were obtained for the volumetric flow rate of the liquid fuel. The fitness of the linear model was expressed by the coefficient of determination of R^2 and the coefficient of adjusted R^2, which were obtained as 0.9487 and 0.9077, respectively. Therefore, the R^2 and adjusted R2 values indicated that the regression model is acceptable. The adequate precision value (P adeq = 11.4931) is greater than 4, which is desirable for the model showing an adequate signal-to-noise ratio of the model.

Table 4. ANOVA results for volumetric flow rate (Q)

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	0.034	4	0.0085	23.12	0.002	Significant
A-tpr	0	1	0	0.0792	0.7896	
B-T1	0.0072	1	0.0072	19.48	0.0069	
C-P1	0.0004	1	0.0004	1.2	0.3226	
D-he	0.0015	1	0.0015	4.01	0.1016	
Residual	0.0018	5	0.0004			
Cor Total	0.0359	9				
Std. Dev.	0.0192		**R^2**	0.9487		
Mean	1.04		**Adjusted R^2**	0.9077		
C.V. %	1.84		**Predicted R^2**	NA		
			Adeq Precision	11.4931		

3.3. Optimization of the liquid fuel using Response Surface Methodology (RSM)

The experimental result for the pyrolysis of plastic waste to liquid fuel was optimized using the numerical optimization in RSM, as shown in Table 4. The optimal value of 83.580 for the product yield was higher than that of Istadi *et al.* (2010) and Islama *et al.* (2013). Furthermore, at the optimal product yield, the volumetric flow rate obtained was 0.966 m^3/s at a production time of 58.375 minutes. Moreover, the inlet temperature to the reactor, inlet pressure to the reactor, and heating rate of the reactor were 379.278^{0}C, 2.419 bar, and 23.363 min./C, respectively. Finally, there is no result from similar studies to compare with the results of volumetric flowrate from this work, which is the contribution made in the study.

Table 4: Optimization result for the pyrolysis of waste plastics

Time of production (t_{pr}) (min)	Inlet temperature to the reactor (C)	Inlet pressure to the reactor (bar)	The heating rate of the reactor (min)	Product yield	Volumetric flow rate	Desirability	
58.375	379.278	2.419	23.363	83.58	0.966	1	Selected

4. Conclusion

The waste plastics identified for the pyrolysis were Polyethylene (PE) (water cans, soft drink cans), Polypropylene (PP) (sachet water, waterproofs) for conversion to liquid fuel. The pyrolysis experiment was designed with Response Surface Methodology in Design Expert software. Four process parameters (time of production, Inlet temperature to the reactor, Inlet pressure to the reactor, and Heating rate of the reactor) were studied, with each parameter being evaluated for its effects on the product yield (Py) and the volumetric flow rate of the liquid fuel (Q). The RSM was used to determine the optimum experimental design matrix for the product yield (Py) and the volumetric flow rate of the liquid fuel.

The result showed that the multiple regression analysis for the pyrolysis of the plastic waste materials indicated linear model equations for the product yield (Py) and the volumetric flow rate (Q) with R^2 values of 0.9625 and 0. 9487 respectively, indicating the fitness of the models. The interaction effects of the parameters showed that an increase in the time of production (tpr) results in a simultaneous increase in the product yield and volumetric flow rate, and an increase in the inlet temperature to the reactor increases the product yield and volumetric flow rate of the liquid fuel. However, increasing the catalysts' weight does not improve the volumetric flow rate without increasing the inlet temperature.

The optimization of the experimental data resulted in the optimal values of 83.580% for the product yield and 0.966 m^3/s for the volumetric flow rate of the liquid fuel were obtained at the time of production of 58.375 minutes, Inlet temperature to the reactor of 379.278^{0}C, Inlet pressure to the reactor of 2.419 bar and heating rate of the reactor of 23.363 minutes.

Contribution to the study

(1) An increase in inlet temperature increases the volumetric flow rates from waste plastics pyrolysis plants.
(2) An increase in catalysts weight depends on the limited increase in inlet temperature.

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