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Research Article

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Optimization and modeling of process conditions for the yield of improved bio oil from co-pyrolysis of corn-cobs and high density polyethylene wastes using central composite design (CCD)

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Abstract In this study, the optimization and modelling of the co-pyrolysis of corn cobs and high-density polyethylene wastes was investigated for the yield of improved bio-oil. The main and interaction parameters were modelled and optimal conditions were predicted using the central composite design (CCD) matrix of design expert stat ease version 12. Temperature, catalyst load, and retention time were important parameters studied at the three levels with bio-oil yield as the response, results were analyzed using analysis of variance (ANOVA) and a regression model was generated. Prepared zeolite crystals were used to catalyze the reactions. The model was found to be significant with p-value <0.05 and only a 0.03% chance the model predictions could have been due to noise. The model precision was accurate with a high R^2 (0.9871). The main effects were all significant with p-values <0.05 and the order of significance was; <0.0001 >0.0008 > 0.0354 for temperature, catalyst load and retention time respectively. Some physical and chemical properties of the bio oil at the optimum condition were determined and indicates the suitability of the bio oil as a fuel source. From the statistical analysis, the study concluded that temperature has the most significant effect on the yield of pyrolysis oil.

Keywords Bio oil yield, waste materials, optimization, modelling, central composite design. Bio fuel

1. Introduction

Any country's economic and social progress is dependent on energy [1, 2]. Many economies around the world are experiencing rapid expansion, resulting in high energy demand as a result, most major economies are currently experiencing energy crisis. Nigeria, like other developing countries, is struggling with energy issues such as environmental pollution caused by fossil fuel exploration and exploitation, depletion of fossil fuel reserves, erratic electricity supply, and failing government policies. These issues can be addressed in Nigeria and other countries across the world by harnessing abundant renewable energy resources such as biomass, solar, wind, and hydropower energy. High energy output using fossil fuels has been used to meet the energy demand [3]. According to scientific research, rising carbon dioxide (CO_2) and other greenhouse gas concentrations are polluting the ecosystem [4, 5, 6]. In this context, agricultural wastes in the form of biomass can play a key role in green renewable energy [7]. Most recent studies are also focusing on waste recycling processes [8]. Globally, the amount of wastes that accumulates in the environment each year approaches billions of tons, posing disposal and health issues [9, 10]. These wastes'

diversity, which includes agricultural biomass, plastics, papers, and edibles, makes them ideal feedstock for high value applications). The waste tonnage of high density polyethylene (HDPE) and paper wastes is also high, and they haven't been appropriately processed as non-biodegradable garbage. [11, 12, 13]. Corn cobs, for example, are ideal for producing large quantities of bio-oil due to their abundance as waste and high combined cellulose and hemicellulose content (about 84 %). According to Bridgwater (2012), a major disadvantage of using biomass is that the properties of the derived bio oil are more similar to biomass than conventional fuel. This is due to the bio oil's high oxygen content, which results in low calorific value and stability when compared to fossil fuel [11]. When biomass is blended with synthetic polymers such as plastics, according to Jiang et al., 2022, the properties of the bio oil can be improved, leading to an increase in the quantity and quality of bio oil [13]. Synthetic polymers contain higher hydrocarbons, less oxygen, and have calorific values comparable to conventional fossil fuels. Pyrolysis has shown to be a successful solid waste management method as well as a source of renewable energy [14, 15]. Pyrolysis is a thermochemical breakdown process that takes place in the absence of oxygen and at temperatures ranging from 300–650 °C degrees Celsius. Because of their availability and low cost, waste materials are commonly used as pyrolysis feedstock [16, 17, 18, 19]. The yield of bio oil as well as the quality of the oil are influenced by several pyrolysis process factors such as temperature, retention time, feedstock weight, and so on [20]. Statistical design of experiments has become more popular than traditional optimization methods in order to save energy, time, and money while also improving the repeatability of results. When the number of factors is enormous, however, a significant number of tests must be conducted in order to achieve trustworthy results [21]. Response Surface Methods (RSM), on the other hand, are frequently employed to reduce the amount of reagents consumed by reducing the number of experiments conducted in order to attain optimization. To find the best conditions and output, the parameters are set at different levels. After variance analysis, a regression equation is created based on dependent variables and their coefficients [22]. Co-pyrolysis is a useful technique; process modeling and optimization will enhance the production of high-quality bio oil and effectively reduce the waste management problem. Although several research efforts have been made on the co-pyrolysis of various biomass with plastics, to the best of the authors' knowledge, the co-pyrolysis of corn cob waste with high density polyethylene using prepared zeolite catalyst and the optimization of the process conditions remain undocumented. This research employs total waste materials to study the optimization and modeling of process parameters in the co-pyrolysis of corn cobs and high density polyethylene wastes using prepared catalysts zeolite catalysts to produce high quality bio oil. The study will develop an effective protocol for effective valorization and management of wastes.

2. Experiment Section

2.1. Materials

Waste materials, corn cobs, paper sludge and high density polyethylene plastics were collected from dumpsites around Abuja in Nigeria. The corn cobs were sundried to reduce moisture before milling to microscopic particle sizes. The corn cobs were washed and demineralized to remove alkali metals and then oven dried at 100 °C for one hour. High density polyethylene (HDPE) wastes were washed ground into smaller pieces. Sludge from waste paper was also collected and washed using distilled water before drying in the oven, it was then calcined for 8 hours at 550°C. The paper sludge-ash was collected and stored.

2.2. Characterization

The proximate analysis followed ASTM guidelines, where as the ultimate analysis was carried out with an Elemental analyzer. Materials were characterized using spectroscopic techniques such as XRF, SEM, and TGA.

2.3. Experimental set-up

A 100 g of corn cob and high density polyethylene ratio 1:1 were placed in a quartz flask. Pyrolysis reactions were carried out in nitrogen atmosphere using an electric heating mantle. Thermocouple was put in the middle of the feedstock mass and connected with the electric heating mantle to control the pyrolysis temperature. A heat exchanger condenser consisting of a low-temperature thermostatic bath was used to collect volatile vapor phase

products in a collecting bottle. The schematic experimental unit for pyrolysis is shown in Fig. 1. Equation 1 was used to calculate the bio oil yield.

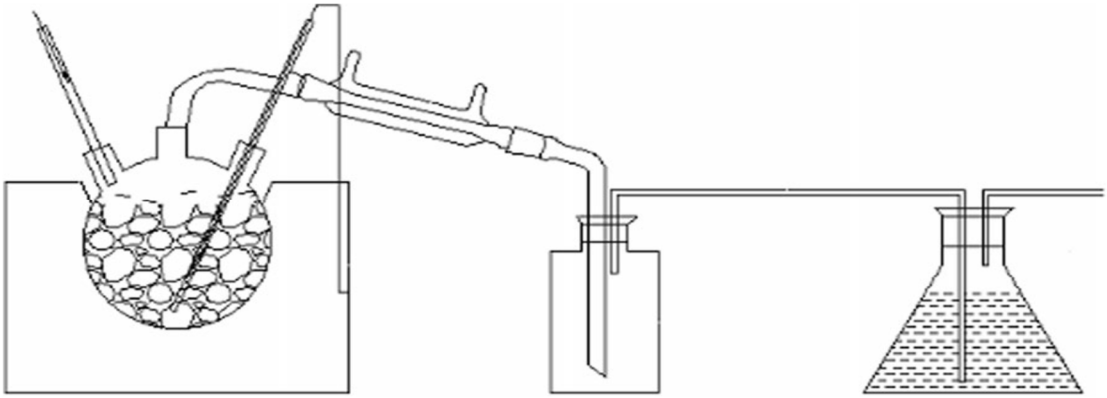

Figure 1: Schematic experimental unit for pyrolysis [5]

$$\text{Bio oil yield} = \frac{\text{Weight of bio oil}}{\text{Weight of (corn cob + HDPE)}} X\ 100 \quad (1)$$

2.4. Optimization process

The design Expert 12.0 software was employed to optimize the pyrolysis reaction, and a face centered model of central composite design (CCD) was used to design the experiments and allow for quadratic modelling of the experimental data. The factors were chosen based on the most important parameters during pyrolysis as determined by studies [17, 18]. Temperature (°C), time (hours), and catalyst load (w. %) were all set to three levels, coded as -1, 0, and +1, respectively. Using equation 2, fifteen experiments were calculated. Three (3) parameters and three intermediate points were calculated.

$$N = 2n + 2 \text{ x } n + m \quad (2)$$

Where n stands for parameter numbers and m for number of middle points. The design of the experiments is shown in Table 1. The calculated fifteen experiments for the co-pyrolysis optimization study had 8 factorial points, 6 axial points, and 3 middle points.

Table 1: Variables and their levels in the experimental design

Variable	Code	Level		
		-1	**0**	**+1**
Temperature (°C)	A	400	500	600
Catalyst load (wt. %)	B	3	5	7
Retention time (hr.)	C	1	2	3

A second-order polynomial equation was used to investigate the effect of the variables' behavior in terms of linear, quadratic, and interaction, as shown in Equation 3.

$$Y = a_o + \sum_{i=1}^{n} a_i X_i \sum_{i=1}^{n} a_{ii} X_i^2 + \sum_{i=1}^{n} 6 \sum_{j>1}^{n} a_{ij} X_i X_j \quad (3)$$

Where Y stands for bio-oil yield, n for the number of experiments conducted, ao, ai, aii, and aij for the constant, linear, quadratic, and interaction coefficients, respectively, and X I and X j for the coded independent components. The significance of each variable alone and in their interactions with one another was determined using the analysis of variance and the p-value [23].

2.5. Bio-oil composition

A gas chromatography mass spectrophotometer (GC-MS) was used to determine the chemical composition of the bio-oil generated under ideal conditions. All of the chemicals found in the bio oil were profiled.

2.6. Catalyst preparation

Using a magnetic stirrer, prepared waste paper sludge-ash was leached with 1 M HCl for 2 hours in a 250 ml flat bottom flask, the residue was then treated with a 3 M sodium hydroxide (NaOH) solution [24]. The flask was heated at 90 °C for 8 hours while stirring under reflux, following which the mixture was filtered. To eliminate NaOH residues, the solid product was rinsed with 1 liter distilled water at 80°C. After which, it was dried for 1 hour in a 100 °C oven. [25, 26].

3. Results and discussions

Table 2: Properties of feedstock

Feedstock	**Corn cob**	**HDPE**
	Proximate analysis (wt. %)	
Moisture	7.14	1.4
Ash content	1.05	3.2
Volatiles	87.7	95.4
Fixed carbon	11.25	1.4
	Elemental analysis (wt. %)	
C	43.58	84.6
H	6.44	12.05
N	0.67	0.03
O	49.30	2.73
S	0.001	0.02
	Inorganics (ppm)	
Ca	7.60	2.40
Si	6.87	7.70
Cr	0.07	0.03

3.1. Physico-chemical properties of feedstock

In pyrolysis reactions, during the heating of a biomass sample, some chemicals are pushed out and are mostly considered volatile matter. Table 2 lists the characteristics of both corn cob and high-density polyethylene (HDPE). High inorganics is observed in the corn cob biomass, calcium an alkaline earth metal is about 7.60 wt. %. Biomass mineral content (ash) has strong catalytic effects on the pyrolysis process and is known to stimulate biomass thermal degradation [27, 28]. Moisture content, on the other hand, has a tendency to reduce the resultant energy of biomass during storage [29]. Moisture obtained was 7.14 and 1.4 wt. % for corn-cob biomass and HDPE respectively. This is acceptable for pyrolysis process as suggested in some studies [30]. Fixed carbon of 11.25 for corn-cob biomass and 1.4 for HDPE was recorded and gives an estimate of the total char that will be produced from both feedstock. Reduced fixed carbon contributes to enhance pyrolysis oil output [31]. Less oxygen was observed in HDPE. The oxygen content in biomass results in decreased calorific value of fuel [32]. The valorization of biomass into energy oil may be hindered by the presence of alkali and alkali-earth metals, the pyrolysis process may also experience catalyst deactivation. Leaching reagents which include water, acids, and bases have proven effective in reducing these inorganics [33]. hence then need to demineralize the corn cob biomass in the present study.

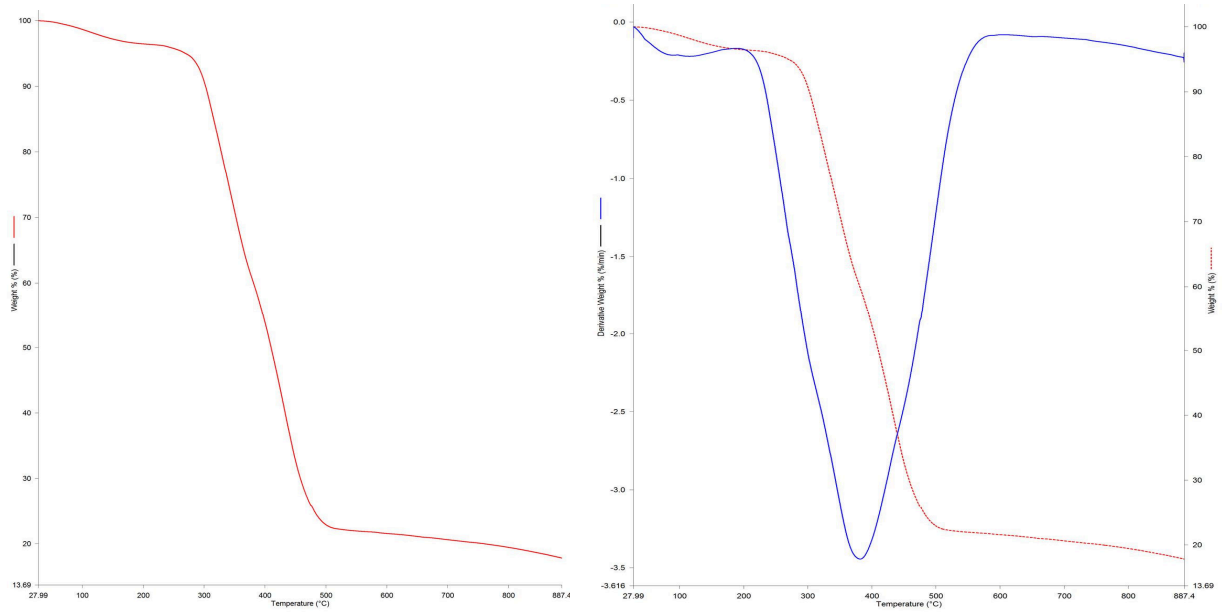

Figure 2: TGA and DTA of Corn-cob

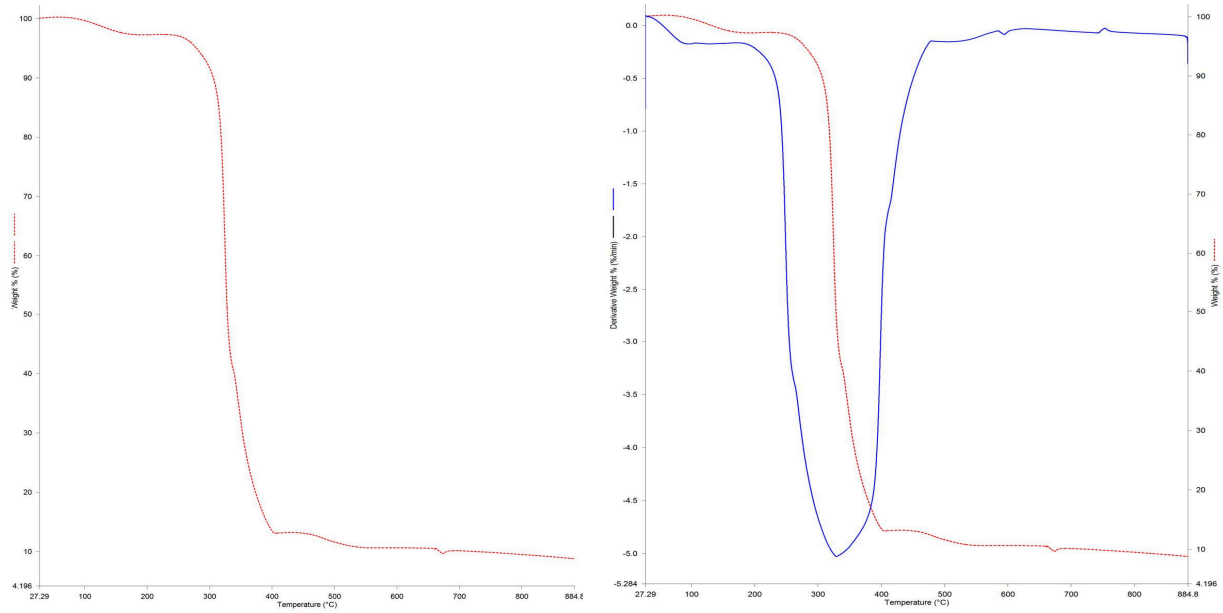

Figure 3: TGA and DTA of HDPE

3.2. Thermal analysis of corn-cob and HDPE feedstock

Thermo gram analysis (TGA) and derivative weight against temperature (DTA) study was employed to look at the thermal decomposition of both corn cob biomass and high-density polyethylene (HDPE). This establishes a link between weight loss and temperature. Figures 2 and 3, illustrate TGA and DTA curves for corn cob and HDPE respectively. Both feedstock revealed different thermal degradation profiles due to their structural variations, with the DTA curve showing them to be homogenous with an endothermic degradation. Their degradation went from ambient temperature to 800 °C with a 20 °C/min heating rate. Corn cob is made up of cellulose, hemicellulose and lignin, therefore all three polymers degraded at different rates. From ambient temperature to around 157 °C, a little percentage of weight loss (5 %) was observed, this was attributed to intrinsic water being released within the corn cob biomass, further degradation was attributed to hemicellulose and cellulose depolymerization. At high

temperature of 290 to 400 ºC, HDPE had 87 wt. % of the mass degraded. The depolymerization of HDPE involves radiant initiation, chain propagation, and radical termination. [34, 15]. Peak temperature was observed as about 400 °C for both feedstock. As a result, the active pyrolytic zone was established as between 400 and 600 °C. Other studies also reported a similar trend [35, 10].

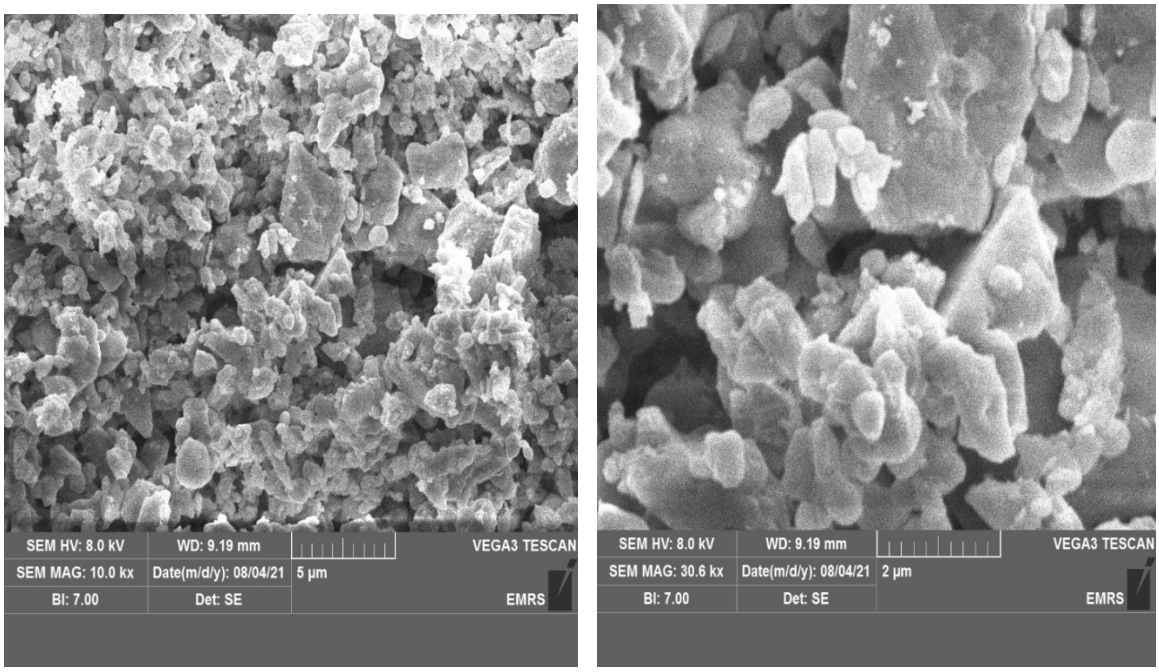

Figure 4: Scanning electron micrograph of Zeolite

3.3. SEM Analysis of zeolite catalyst

Figure 4, shows SEM micrographs of the prepared zeolite at two magnifications: 10.0 kx and 30.6 kx. The prepared zeolites have characteristic surfaces of the faujasites type, a mesoporous network of cage like crystals with large pore spaces between them, although this is more pronounced at certain magnifications [36, 37].

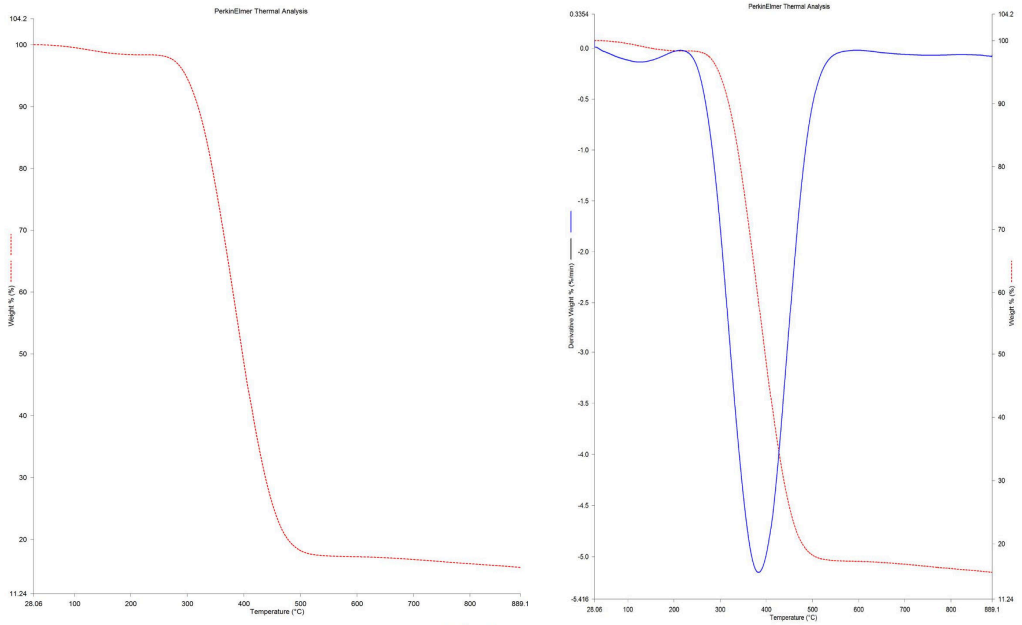

Figure 5: TGA graph of zeolite FAU-Y

3.4. TGA analysis of zeolite catalyst

The thermal behavior of prepared zeolite was investigated, with the results displayed as TGA and DTG curves in Figure 5. At around 100-200 °C, an initial weight loss from 100 wt. % to around 97 wt. % was observed, which was attributed to weakly bound water molecules desorption. A second weight loss occurred around 300-400 °C, leaving the weight of zeolite at 60 wt. %; was attributed to thermal degradation of inorganic components of the alumina-silicate structure, a complete degradation of the zeolite structure occurred when the material remaining was 20 wt.% from 500-900 °C. At around 380 °C, the DTG curve exhibits a single downward slope, indicating that the reaction is endothermic and the compound is homogeneous in nature [35].

Table 3: Experimental design for Corn-cob and High density polyethylene (HDPE) co-pyrolysis

Experimental Run	Temperature (^{0}C)	Catalyst (wt. %)	Retention time (hr.)	Bio-oil yield
3	400	3	1	20
5	400	3	3	20
14	400	5	2	21
11	400	7	1	21
6	400	7	3	22
8	500	3	2	22
2	500	5	1	22
9	500	5	2	22
1	500	5	3	22
12	500	7	2	23
7	600	3	1	23
4	600	3	3	23
10	600	5	2	23
13	600	7	1	23
15	600	7	3	24

3.5. Optimization process

The amount of bio-oil produced from the co-pyrolysis of corn-cob biomass and high-density polyethylene (HDPE under various reaction conditions is presented in Table 3. Various yields of bio-oil were obtained in this study, ranging from 20.0 wt. % to 24.0 wt. %. These variations are attributed to the availability of condensable volatile matter at different reaction conditions [10]. A model was developed for optimizing the yield of bio oil by fitting a second-order polynomial function as shown by equation 4. The main and interaction effects of the three experimental factors; temperature (A), catalyst load (B), and reaction time (C), were modeled using response surface methodology. The main factors, their interaction, and quadratic factor effects were found to be significant in determining the yield of bio-oil based on their low p-values (<0.05). The terms that at 95 % confidence interval were found to be statistically acceptable were used in the model. The positive or negative sign of the coded terms determines the positive or negative interaction effects of terms [38].

Bio-oil yield = +22.18 +1.20A +0.5000B +0.2000C -0.2500AB +0.0000AC +0.2500BC
-0.2222A2 +0.2778B2 -0.2222C2 (4)

The model equation in terms of coded factors can be used to make response predictions for given levels of each factor. The high factor levels are coded as +1, while the low factor levels are coded as -1. The coded equation can be used to determine the impact of the factors on the response by comparing the factor coefficients. Because of its huge coefficient, coded factor (B) corresponding to catalyst load was shown to have the greatest influence on bio oil yield in the model equation. Table 3, shows that the ideal bio-oil yield of 24.0 wt% was achieved for the parameters; temperature (600 ^{o}C), catalyst load (7.0 wt. %) and retention time (3hrs). These conditions are close to theoretical optimized reaction conditions; temperature (479.55 ^{o}C), catalyst load (6.75 wt. %) and retention time (3.0 hrs). The model predicted a yield of 22.72 wt. %. This amount is close to the yield obtained experimentally. The plot of model

predicted yields and experimentally obtained yields illustrates a straight line graph as shown in Figure 6. It shows the model predicted yields to be 99% accurate. This confirms that the model is suitable for predicting and modelling of the bio-oil yield [39, 40].

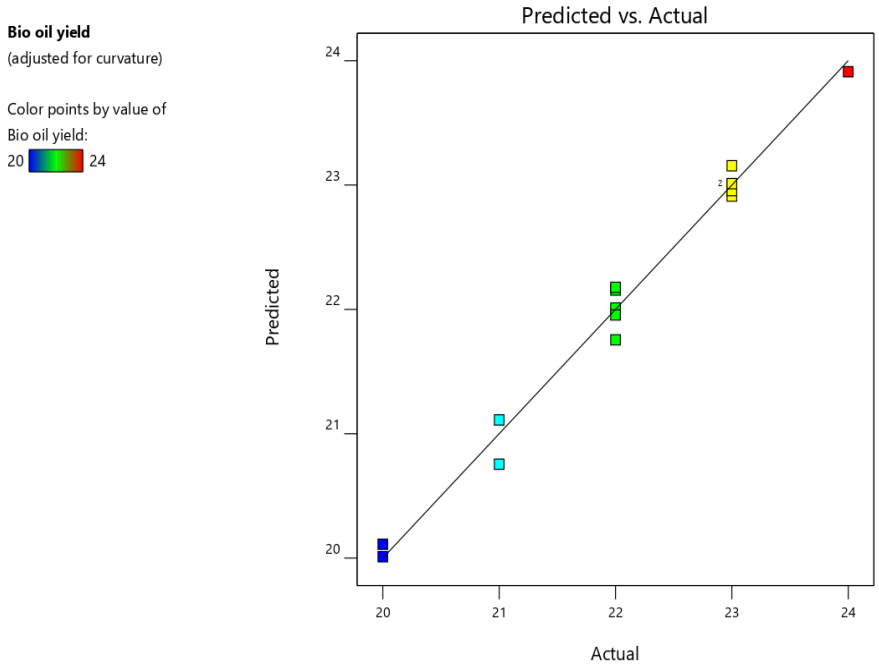

Figure 6: Plot of predicted against actual bio-oil yield

Table 4: Analysis of variance (ANOVA) for optimized parameters of Corn-cob and HDPE co-pyrolysis

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	18.69	9	2.08	42.47	0.0003	significant
A-Temperature	14.40	1	14.40	294.55	< 0.0001	
B-Catalyst load	2.50	1	2.50	51.14	0.0008	
C-Retention time	0.4000	1	0.4000	8.18	0.0354	
AB	0.5000	1	0.5000	10.23	0.0240	
AC	0.0000	1	0.0000	0.0000	1.0000	
BC	0.5000	1	0.5000	10.23	0.0240	
A^2	0.1270	1	0.1270	2.60	0.1680	
B^2	0.1984	1	0.1984	4.06	0.1001	
C^2	0.1270	1	0.1270	2.60	0.1680	
Residual	0.2444	5	0.0489			
Cor Total	18.93	14				

R^2	0.9871
Adjusted R^2	0.9638
Predicted R^2	0.8981
Adeq Precision	21.6026
Std. Dev.	0.2211
Mean	22.07
C.V. %	1.00

3.6. Analysis of variance (ANOVA)

Using the quadratic model in central composite design (CCD), analysis of variance (ANOVA) was used to explain the effect of reaction parameters on bio-oil yield. Table 4 shows the ANOVA results for the bio oil yield response. Significant terms make a good model [41, 40]. When the F-value is on the high side, the predicted model's reliability is deemed to be appropriate. When the p-values are on the low side, the predicted model's significance is adequate. The model's F-value and p-value was 42.47 and 0.0003, respectively, indicating the significance of the regression model. The high F-value also indicates that the model predictions have only a small possibility (0.03 %) of being attributed to noise. This agrees with the model's low p-value. The coefficient of determination R^2 indicates that the model is fit with good precision. The high value of R^2 (0.9871) for the model analysis suggests that the quadratic model used in this study was precise. The adjusted R^2 and predicted R^2 are used to check for the adequacy of the predicted model. With a difference of less than 0.2, the adjusted R^2 of 0.9638 agrees with the predicted R^2 of 0.8981. The results are consistent with those of other investigations [15, 42]. Adeq precision measures the signal-to-noise ratio, and a value above 4 is desirable. The model's Adeq precision value is 21.6026, which is higher than the permissible limit of 4, indicating that it is adequate for navigating the design space [43]. A good model should have a large number of significant model terms, model terms with p-values less than 0.05 are considered significant [40]. Temperature, catalyst load, retention duration, and the interactions; temperature vs catalyst load, catalyst load versus retention time, etc. are considered significant model parameters in this study. Because their p-values are 0.0001, 0.0008, and 0.0354, respectively, the order of their significant effect on bio-oil yield is A > B > C. The interaction effect between temperature and Catalyst load (AB) and between catalyst load and retention time (BC) was of equal significance (0.0240) while that of temperature and retention time (AC) was insignificant (1.0000). Similarly the quadratic effect of temperature (A) and retention time (C) was of equal significance (0.1680) while that of catalyst load (B) was insignificant (0.1001).

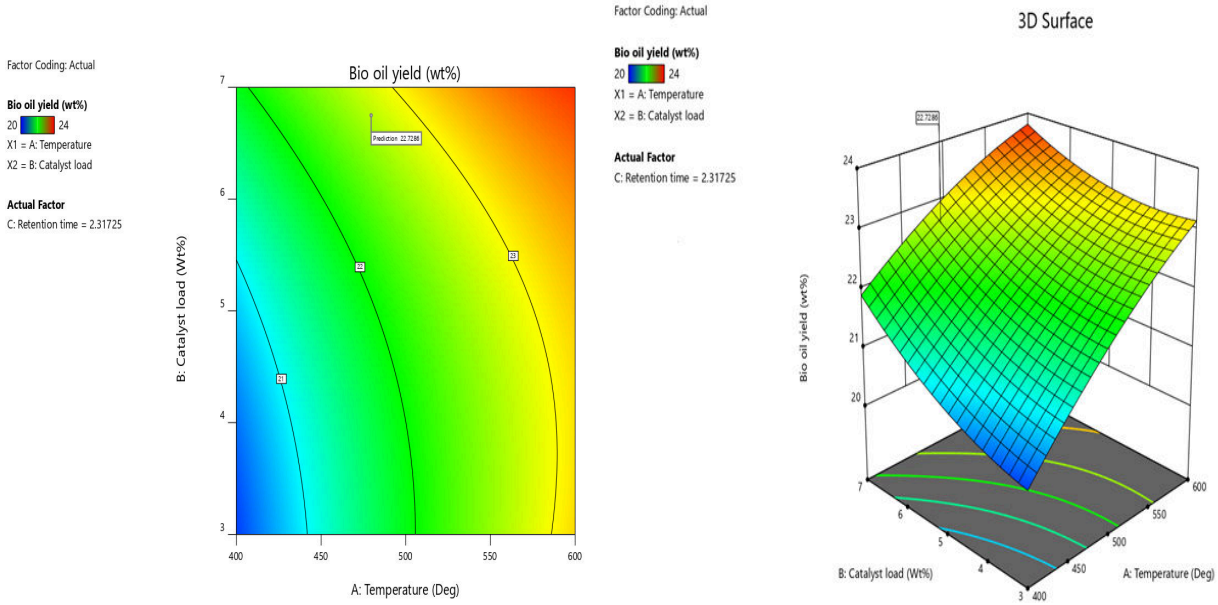

Figure 7: Response surface and contour plot for catalyst load vs temperature against bio oil yield

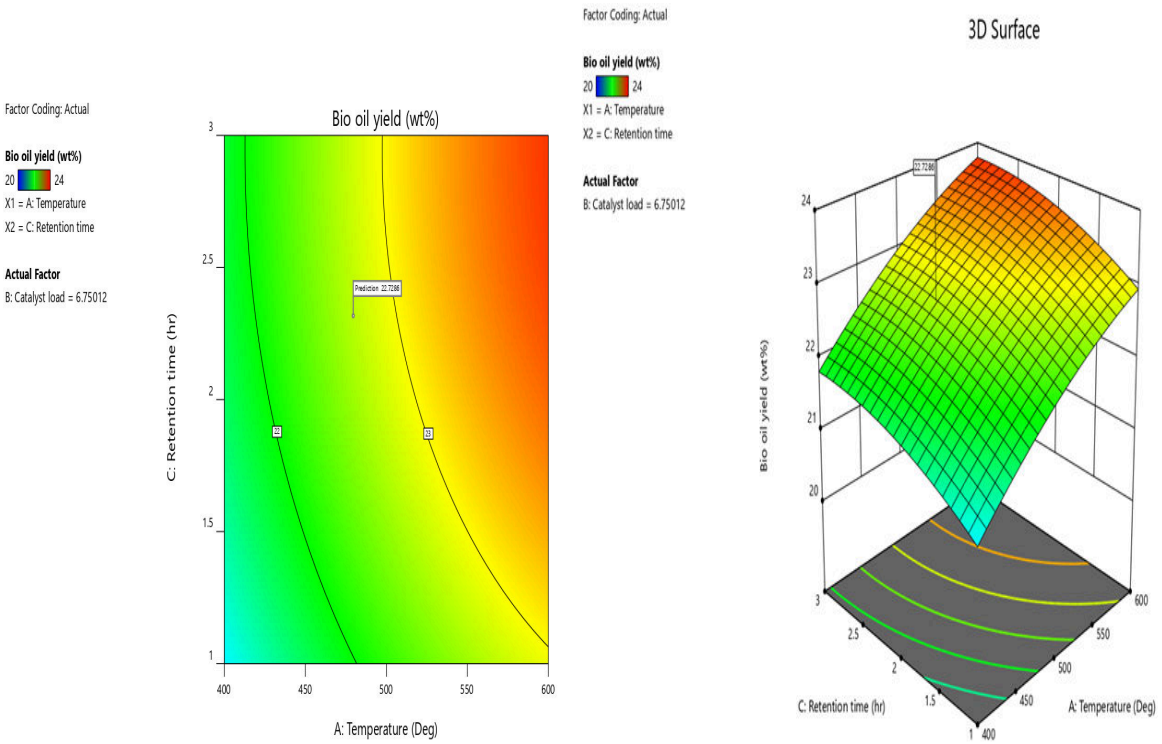

Figure 8: Response surface and contour plot for retention time vs temperature against bio oil yield

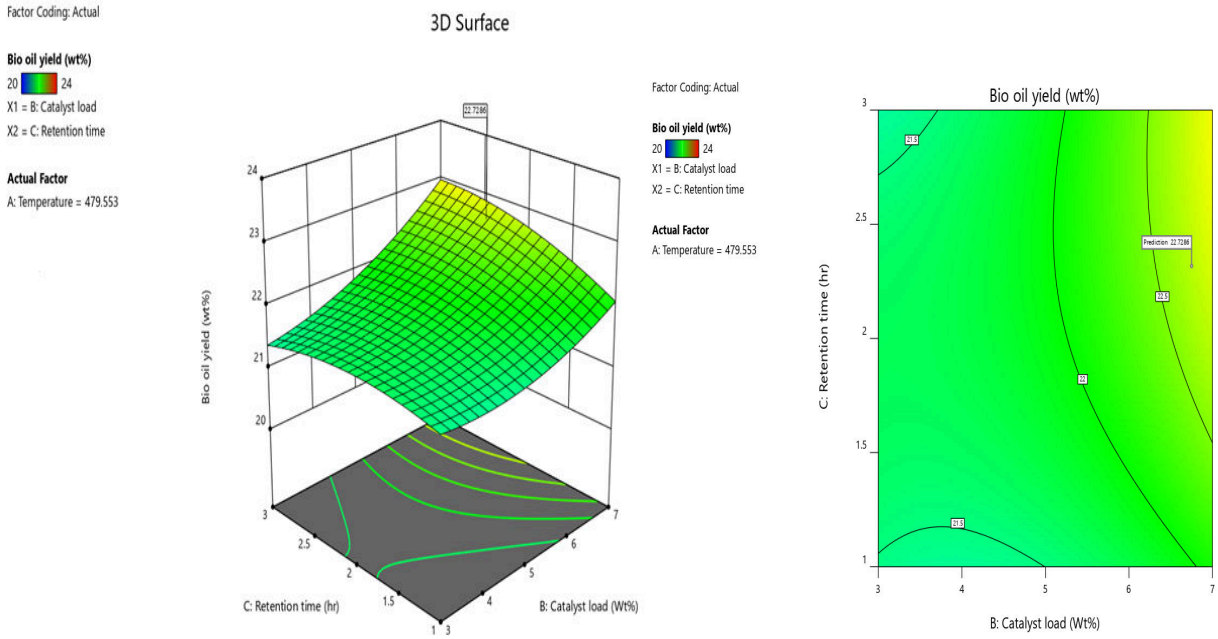

Figure 9: Response surface and contour plot for catalyst load vs retention time against bio oil yield

3.7. Response surface plot interaction of reaction parameters (Co-pyrolysis)

Figures 7, 8 and 9, illustrate bio oil yields plotted as a function of examined parameters and their significant influence on the quantity of bio-oil obtained respectively. A p-value <0.05 indicates a significant interaction. The contour plot's red regions represent areas with high bio-oil yields, while the other colors indicate areas with lesser

bio-oil yields. Figure 7, shows the interaction between temperature (A) and catalyst load (B). At high reaction conditions of both parameters, bio-oil yields continued to increase. The contour plot shows that high bio-oil yields can be obtained by using high reaction conditions. This is consistent with the obtained p-value (<0.05) shown in Table 4 for their coded interaction (AB). As a result, their interaction is regarded as significant. The interaction of volatile components within catalyst pores is enhanced by increasing the amount of catalyst particles, which favors optimization. [10, 44, 45]. Figure 8, illustrates the interaction between temperature (A) and retention time (C) and is consistent with the contour plot of. A negative synergy between both parameters was observed, with the bio-oil yield dropping above 2.5 wt. % catalyst while temperatures above 600 °C favoured high bio oil yield. This result agree with the p-value (1.000) for their coded interaction shown in Table 4. This shows that their interaction is insignificant. Figure 9, represents the interaction between catalyst load (B) and retention time (C). High values of both reaction conditions resulted in high bio-oil yield. A similar trend can be seen in the contour plot. The p-value < 0.05 obtained for their coded factors (BC) as presented in Table 4 suggests that the parameters interacted significantly. Secondary reactions will be limited if reactions are concluded within optimal residence time [46, 47].

3.8. Optimization and validation

The model's ideal reaction conditions as well as the results of the validation experiment for the yield of bio oil is summarized in Table 5. At the reaction conditions of temperature (479.55 ^{o}C), catalyst load (6.75 wt. %), and retention time (3.0 hrs.), a high bio oil yield of 22.72 wt. % was predicted. Under these ideal conditions, the model's accuracy was verified. A mean bio-oil yield of 22.48 wt. % was obtained from experimental reaction, which was close to the predicted result and validated the results obtained from the predicted model.

Table 5: Experimental validation for bio-oil yield

Experiment	Temperature (°C)	Catalyst load (wt. %)	Retention time (min)	Bio-oil yield	Error
Predicted	479.55	6.75	3.0 hrs.	22.72	0.001
Validation	479.55	6.75	3.0 hrs.	22.48	0.012

Table 6: Physical properties of bio oil

Property	Unit	Corn cob-HDPE	Conventional diesel
Density(15^{0}C)	(g/cm^{3})	0.814	0.815 - 0.870
Viscosity (40^{0}C)	(Cst)	0.91	2.0 – 4.5
Acid value	(mgKOH)	10.8	0.015 - 0.08
Flash point	(^{0}C)	45	52
Cloud point	(^{0}C)	-47.6	-37
Calorific value	(MJ/kg)	35.2	43.06

Characteristics of bio oil

The bio oil obtained from the pyrolysis of corncobs and high density polyethylene ratio (50:50) at optimum reaction conditions of 600 °C temperature, catalyst load 7.0 wt. %, and retention time of 3.0 hours was employed in the determination of physical and chemical characteristics. A summary of the characterization of bio oil and comparison with conventional diesel is given in Table 6 . The Density was 0.814 g/cm^{3} which is below the range of 0.815 - 0.870 for conventional diesel fuel standards (ASTM D975 2013). The acid value of the obtained bio oil was 10.8 mgKOH which is higher than conventional diesel standard. The high acid value indicates the presence of organic acids. The viscosity of the bio oil was 0.91Cst which is lower than the 2.0 – 4.5 for diesel. Flash point is an important combustion property of fuel. The flash point for the bio oil was 45 °C which is lower than 52.0 for conventional diesel. The cloud point of the bio oil was found to be -47.6 °C which is better than -37 °C for diesel. The calorific value indicates the energy of fuel, a high energy fuel may be sufficient in little amounts. The calorific value of the bio oil was found to be 35.2 MJ/kg this was lower than conventional diesel. The physicochemical

properties indicate that the synergistic catalytic interaction of the feedstock owing to series of deoxygenation and hydrogenation reactions had a positive effect on the properties of the obtained bio oil.

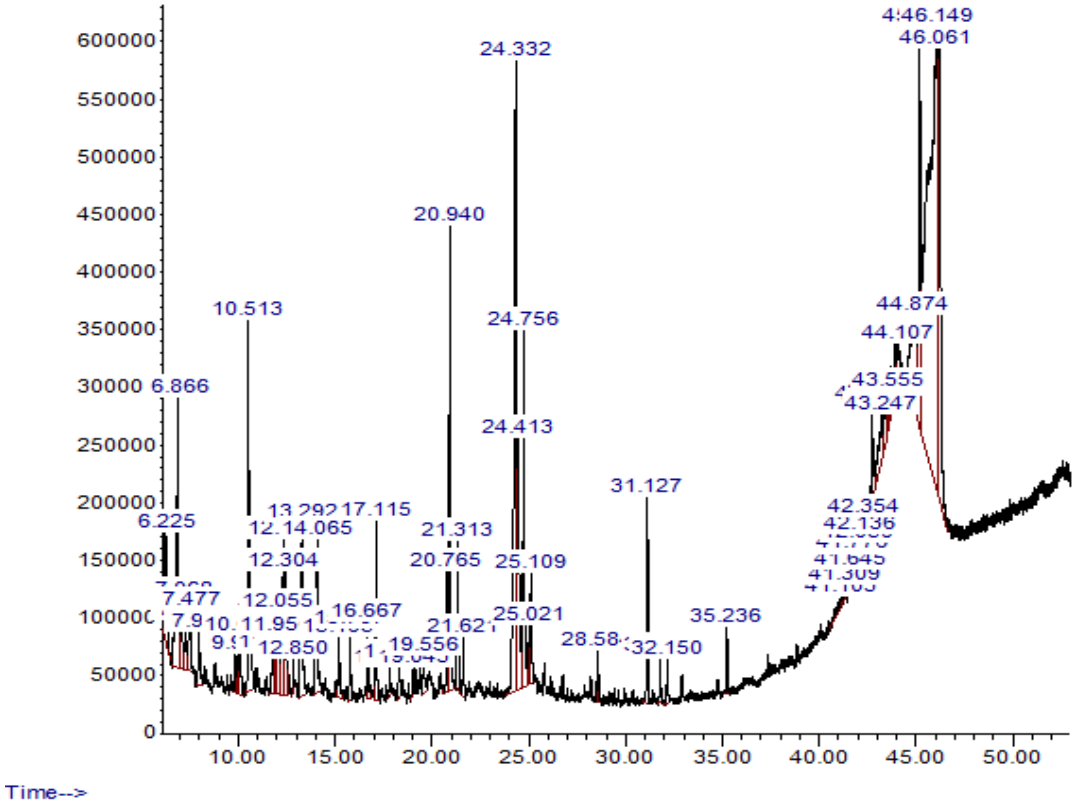

Figure 10: GC-MS chromatogram of bio oil

Table 7: Summary of chemical composition of bio oil

Compound	Area %
Hydrocarbon	14.9723
Amine	25.3429
Phenol	8.1743
Ester	14.0979
Carboxylic acid	22.4543
Aldehyde	2.3674
Others	6.6404

3.10. Composition of bio-oil

Table 7, summarizes the composition of bio-oil obtained at optimum conditions and analyzed using gas chromatography mass spectrophotometer (GC-MS), the chromatogram is shown in Figure 10. From the profile, hydrocarbons, amines, phenols, oxygen-containing compounds (esters, carboxylic acids, aldehydes), and other compounds were identified as major components in the bio-oil. The presence of these compounds may be responsible for the determinations observed in some of the properties of the bio oil. The presence of carboxylic acids for instance will affect the acid value of the bio oil, while oxygen containing compounds will lower the hydrogen to carbon ratio and in turn the calorific value. Synergistic effects between corn cobs and HDPE observed in the co-pyrolysis process suggests that hydrocarbon radicals created by polyethylene degradation might be responsible for the substantial amount of hydrocarbons. The presence of hydrocarbon improves the calorific value, it also suggests the bio oil to be a promising energy source.

4. Conclusion

From the results of optimization and modelling of the co-pyrolysis process for corn cobs and high density polyethylene (HDPE), it is possible to achieve high bio-oil yields with improved properties at the optimal reaction conditions obtained by the suggested model in this study. The model and main effects were all significant at p-value <0.05. A maximum bio-oil yield of 22.72 % was predicted by the model at 479.55 °C temperature, 6.75 wt. % catalyst load and 3.0 hours retention time. The predicted bio-oil yield was close to experimental validated bio oil yield. Having a good fit and precision, the model was suitable in navigating the design space and also for prediction and modelling of corn cobs and HDPE co-pyrolysis. The characterization of the bio-oil obtained at optimum conditions showed it has high energy value and most of its properties are within acceptable fuel standard. Further research involving various feedstock ratios can be carried out in order to obtain bio oil that can be used as a diesel fuel substitute and to study the possibilities of pyrolysis in the management of these wastes to ameliorate the problem of solid waste disposal.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper. Also, they declare that this paper has not been published elsewhere.

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