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Determining the Optimal Product Yields from the Pyrolytic Conversion of Oil Palm Trunk

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Abstract

Experimental and analytical methods were employed to obtain the combination of parameters to optimise product yields from the pyrolysis of oil palm trunk (OPT). Sample (0.5kg) of oven-dried OPT was loaded into a steel retort, and the retort interior was rendered airtight. The retort was then placed into the furnace chamber and the OPT was pyrolysed for 10, 15, 20, 25 and 30 minutes at 300 °C. This was repeated for temperatures of 400, 500, 600 and 700 °C and in each case, the quantities of char, tar and pyro - gas produced were determined. Full-Factorial Design (FFD), comprising two factors – temperature and duration of pyrolysis – at three levels, was employed to study the pattern of char, tar and pyro – gas yields. Thirteen experimental runs resulted from the FFD, with a minimum product yield of 0.7 % and maximum product yield of 98 %. Response surface methodology was used to analyse the results of the FFD of the product yields of OPT. The optimum conversion yields of oven-dried weight of OPT of char, tar and gas products at their respective pyrolysis conditions were 98 wt% char at 300 °C and 10 min., 39 wt% tar at 310 °C and 28 min., and 50 wt% gas at 700 °C and 30 min. The results of the work show that OPT can be readily pyrolised to obtain optimum yield of gas, tar and char.

Keywords: Pyrolysis, Oil-palm Trunk, Gas, Tar, Char and Response surface methodology.

1.0 Introduction

The need to focus much more on renewable energy sources arose as a result of escalating costs of petroleum products, significant decrease in the quantity of crude oil reserves and environmental degradation caused during exploitation, processing and uses of petroleum products. Energy shortage being experienced in many countries is due to rapid increase in population and industrialization. There is the need to preserve crude oil reserves for use in the petrol-chemical industries while the renewable sources of energy be increasingly tapped, for use, as fuel in domestic and also industrial appliances.

Biomass appears to be an attractive renewable energy resource, not only because of its potential as a domestic cooking fuel but as a more environmentally friendly renewable fuel (Askew and Holmes, 2001; Sims *et al*., 2003; Sims, 2004). It is important to take stock of energy sources, conserve them and consider the possibility of harnessing other sources, which are not much utilized at present (Granada *et al*., 2002). Agricultural residues offer more potential for renewable energy resources. With advances in biotechnology and bioengineering; some resources, which could have been classified as waste, now form the basis for energy production (McKendry, 2002; Demirbas, 2007).

Biomass energy consumption has been increasing and has roughly accounted for about 14% of total world energy consumption, with developing countries accounting for about 75% of the biomass utilization (Matti, 2004; Yang *et al*., 2005; Zanzi *et al*, 2002; Gercel, 2002). Biomass readily subjects itself to thermo-chemical conversion process to produce fuel and chemical products. The thermo-chemical conversion processes include direct combustion of biomass. By this, biomass is burnt usually in open air to provide heat for some domestic and industrial processes. The direct burning of biomass has been used to power steam boilers (Chopra and Jain, 2007).

A number of thermo-chemical methods can also be used in converting biomass into useful products. This includes gasification, incineration, anaerobic digestion and pyrolysis (Babu, 2008). Among the these conversion processes, pyrolysis is a viable process for biomass upgrading by cracking polymeric structure of lignocellulosic materials and converting them into a volatile fraction consisting of gases, vapours and tar components and a carbon rich solid residue (char) fractions (Luangkiattikhun et al. 2007). The volatile fraction can be used as a fuel or as a chemical feedstock. The remaining solid fraction can find several applications, such as in the production of activated carbon or used directly as a solid fuel. OPT are abundant on the farms of the rain forest and savannah areas of Nigeria. They constitute a waste disposal problem in oil-palm plantation. Converting these solid residues into useful products will complement the depleting energy resources and make some useful chemicals available to industries especially in the rural areas in Nigeria (Jekayinfa and Omisakin, 2005; Osaghae, 2009; Matti, 2004).

2.0 Methodology

2.1 Oil-palm trunk (OPT) material preparation.

Oil-palm trunk used for the pyrolysis experiments in this study was obtained from an oil-palm industry in Ife

Odan, Osun State, Nigeria. The residues were cleaned in order to remove foreign particles such as stones, leaves, debris and other unwanted components. The foreign particles were removed from the residues by handpicking. The weight of the sample (W_1) was measured using Ohaus top loading digital weighing balance (Model: PA4102, range: 0-4100 g, Ohaus company, Manufactured in Switzerland) and then oven-dried at a temperature of 103±2 °C until constant weight (W_2) was obtained in accordance with official methods of the ASTM D5373-02 (2005).

2.2 *Methods.*

Pyrolysis experiments was carried out to determine the combination of parameters that gave the optimal product yields from OPT. 0.5 kg of dried OPT were fed into the retort. The retort was placed into the furnace and pyrolysed at around 300, 400, 500, 600 and 700 °C. The retort was connected through a pipe to the condensate receiver which was placed in a chiller for the quick recovery of the condensable products (tar), and from the condensate receiver the uncondensed pyrolytic gas moved through a rubber hose into the gas collection unit.

The char in the retort and the condensate in the condensate receiver were collected and weighed using Ohaus top loading digital weighing balance. The weight of gas was evaluated by subtraction. The percentage of product yields was calculated from equation 1.

$$\text{Percentage product yields } Y = \frac{mass\ of\ product}{mass\ of\ sample} \times 100 \qquad (1)$$

2.3 *Experimental Design*

Full-Factorial Design (FFD) of response surface methodology was used for the experimental design to optimise the pyrolysis product yields from OPT. FFD consisted of a two-factor, three-level design comprising the pyrolysis temperature and pyrolysis duration of the feedstock as the independent variables while pyrolysis product yields consisting of solid product (char), the liquid product (tar) and the gaseous product (gas) as the dependent variables or the responses were used as shown in Table 1. A centre point for the design was selected with factors at a level of medium standards as shown in Table 2. With the centre point design selected, the actual values of each factor were calculated. The design was based upon the symmetrical selection of variation about the centre point and levels of variations were chosen to be within the boundary range of the variables. The coded and actual values of the variables at various levels and responses are given in the Table 2. Three replications were carried out for all experimental design conditions and the average recorded. Thirteen experimental runs were carried out and the order of the experiment was fully randomised to reduce the effect of the unexplained variability in the observed responses due to extraneous factor as recommended by Singh *et al* (2003).

Table1: Experimental Factors and Responses

Type	**Variables**	**Symbols**
Factors	Temperature	A
	Duration	B
Responses	Char yield	Y_c
	Tar yield	Y_t
	Gas yield	Y_g

Table 2: Experimental Values of Coded Levels

	Coded Levels		
Factors	**-1**	**0**	**+1**
A (^{0}C)	300	500	700
B (Min)	10	20	30

2.4 *Analysis of Data and Response Equations.*

Regression Models were developed for OPT product yield and each of the product yield as a function of the two factors. The Design Expert 6.0.8 software was used to analyse the data obtained from the pyrolysis of OPT for developing response equations, Analysis of Variance (ANOVA), to generate surface plots and determine optimum pyrolysis conditions and product yield using its optimization toolbox. In multiple regressions, as in the present case, R^2, which is the square of the adjusted coefficient of determination and standard error are the indices. *F* statistics shows the significance of overall model while the t-statistics tests shows the significance of each of the variables of the model. The Functions was assumed to be approximated by a second degree polynomial equation.

$$Y = b_0 + \sum_{i=1}^{m} b_i x_i + \sum_{i=1}^{m} b_{ii} x^2{}_i + \sum_{i \neq j}^{m} b_{ij} x_i x_j \tag{2}$$

where *Y* is the predicted response, b_0 is the value of the fitted response at the centre point, and b_i, b_{ii}, b_{ij} are linear, quadratic and cross product regression terms respectively. *m* is the number of factors considered in the study which is equal to 2.

2.5 *Optimization of the Product Yields.*

A nonlinear programming problem of the form of equation 2 was formed from the vector of equation 2 as shown in equation 3. The optimization problem statement to maximize the product yields was formulated as shown in equation 3.

$$\text{Maximize } Y = f(AB) \tag{3}$$

Subject to

$$L_A \le A \le U_A$$

$$L_B \le B \le U_B$$

Where Y is the product yields, L_i is the lower limit of the factors and U_i is the upper boundary of the factors. The line search problem stated in eq. 2 was embedded and solved in the optimization routine of design expert 6.0.8 version to obtain the optimal yields and the corresponding optimal process variables.

3.0 Results and Discussions

Based on t-test, the regression coefficient that are not significant at 95% confidence level were discarded while only those ones that are significant were used to develop the final model equation.

3.1 *Response Equations for OPT Product Yields.*

The effect of FFD on the OPT pyrolysis product yields (char, tar and gas yields) is as shown on Table 3 that was subsequently used to fit the response equations for product yields. Multiple regression analysis was used as tools of assessment of the effects of two or more independent factors on the dependent variables (Boomee *et al*, 2010). The coefficients of determination (R^2) is a measure of the total variation of the observe values of the product yields about the mean explained by the fitted model (Shridhar *et al,* 2010). The factors of the models, their parameters estimates and the statistics of the estimates for the best functions adopted, taking into consideration all main effects, linear, quadratic, and interaction for each model are as shown on Table 4. The coefficients of determination (R^2) for the responses (char, tar and gas) were 0.9936, 0.9860 and 0.9583 respectively. The coefficient of determination (R^2) were high for response surfaces, and indicated that the fitted quadratic models accounted for more than 89% of the variance in the experimental data. Base on the p values, the regression coefficient that were significant at $p<95\%$ were selected for the models that resulted in equations 4 - 6. Analyses of variance (ANOVA) were conducted to evaluate the adequacy and consistency of the models using F-statistic. The analysis of variance of the models is presented in Table 5. The results presented on Table 5 showed the F-values for char, tar and gas as 376.24, 169.53 and 56.22 respectively. These values were significant at $p< 0.05$ indicating good model fit.

$$Y_{C_{OPT}} = 36.91 - 11.05A - 25.99B + 4.66A^2 + 16.01B^2 + 3.70AB \qquad R^2 = 0.9936 \tag{4}$$

$$Y_{t_{OPT}} = 31.22 + 12.18A - 110.5B^2 - 6.96AB \qquad R^2 = 0.9860 \tag{5}$$

$$Y_{g_{OPT}} = 31.94 + 10.44A + 13.81B - 4.75A^2 - 5.20B^2 + 3.26AB \qquad R^2 = 0.9583 \tag{6}$$

Where: $Y_{C_{OPT}}$ = Yield of char from OPT (Wt%)

$Y_{t_{OPT}}$ = Yield of tar from OPT (wt%)

$Y_{g_{OPT}}$ = Yield of gas from OPT (wt%).

A = Temperature (°C)

B = Time (Minutes).

3.2 *Optimization of Pyrolysis Process.*

Response surface methodology was used for the optimization of the pyrolysis process of the feedstocks (OPT) and for understanding the factors affecting the pyrolysis process. The models were useful for indicating the direction in which to change the variable in order to maximise the yields of char, tar and gas. The multiple regression equations were solved using Design Expert 6.0.8. The regression equation was optimized for maximum value, to obtain the optimum conditions. The optimum values obtained for OPT pyrolysis product yields and their respective pyrolysis conditions are: 98.11% char at A = 300.14°C and B = 10.01 minutes, 38.77% tar at A = 310.12°C and B = 28.22 minutes and 49.50% gas at A = 700°C and B = 30 minutes.

The linear effects of temperature and time are the primary determining factors of the responses as shown in Table 4. Pyrolysing time as a single factor was the most influential factor, because of its higher F-value. The time at which pyrolysis process was conducted is highly significant ($p<0.05$) with an F-value of 1287.55 as shown in Table 4.

Figures 1-3 show three-dimensional (3D) surface plot and accompany contour plot for the relationship between the independent and dependent variables for chosen model. The cubic response surface plot shown in Figure 1(a) depicts the effect of the pyrolysing temperature and time on the OPT char yield. From the contour plot in Fig 1(b) it is observed that the surface area decreases as the pyrolysing temperature and time increase. Fig 1(b) shows that, char yield of OPT decreases as the pyrolysing temperature and time increase. Mohamad (2008) reported that, the decrease in char yield with an increase in pyrolysing temperature could either be due to secondary decomposition of the char residues or through the greater primary decomposition of the OPT at higher temperatures.

The cubic response surface plot shown in Figure 2(a) depicts the effect of pyrolysing temperature and time on the OPT tar yield. It was observe from the contour plot in Figure 2(b) that the surface area increases as the pyrolysing temperature and time increases. From Figure 2(a) cubic response surface indicates that the tar yield increases as the pyrolysing temperature and time increase to optimum condition while further increase in pyrolysing temperature and time led to decrease in tar yield. This shows that, there was a mutual interaction between the pyrolysing temperature and time on tar yield. Pyrolysis process at higher temperature might have led to more tar cracking resulting into higher gas yield and lower tar yield.

The cubic response surface plot shown in figure 3(a) depicts the effect of pyrolysing temperature and time on the OPT gas yield. It is observed from the contour plot in figure 3(b) that the surface area increases as the pyrolysing temperature and time increased. From figure 3(a) the cubic response surface indicates that the gas yield increases as the pyrolysing temperature and time increase. The increase in gaseous products as the reaction temperature increases might be due to the secondary cracking of the pyrolysis vapours at higher temperatures, or secondary decomposition of the char at the higher temperatures (Mohamad, 2008).

Table 3: Full Factorial Design Arrangement and Responses for OPT

Exp. No.	**Coded Level**		**Actual Values**		**Responses**		
	A(°C)	**B(min)**	**Temp. (°C)**	**Time(min)**	$Y_{C_{OPT}}$	$Y_{t_{OPT}}$	$Y_{g_{OPT}}$
1	0	-1	500	10	80.89	8.12	10.99
2	-1	1	300	30	39.07	38.75	22.18
3	-1	-1	300	10	98.08	1.23	0.69
4	1	-1	700	10	67.10	15.31	17.59
5	0	0	500	20	36.27	30.86	32.87
6	1	1	700	30	22.87	25.00	52.13
7	0	0	500	20	36.27	30.86	32.87
8	0	0	500	20	36.27	30.86	32.87
9	1	0	700	20	33.62	34.63	32.75
10	0	0	500	20	36.27	30.86	32.87
11	0	1	500	30	28.17	34.00	37.83
12	-1	0	300	20	52.74	30.28	16.98
13	0	0	500	20	36.27	30.86	32.87

A = Temperature (°C)
B = Time (min)
$Y_{C_{OPT}}$ = Yield of char from OPT (wt%)
$Y_{t_{OPT}}$ = Yield of tar from OPT (wt%)
$Y_{g_{OPT}}$ = Yield of gas from OPT (wt%)

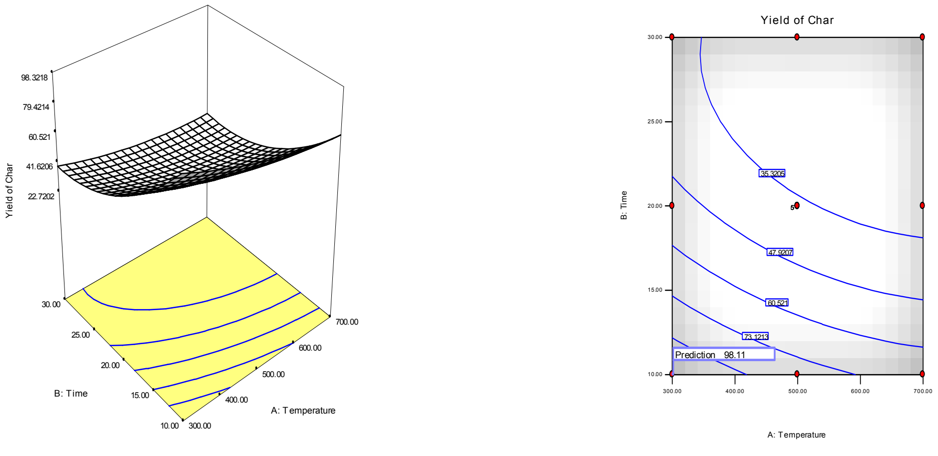
Table 4: Parameter Estimation from Regression Analysis of OPT

Estimated Coefficient of the fitted model for properties based on t-statistics				
Responses	Model Factors	Coefficients	F-Values	p-Values
Yield of Char $Y_{C_{OPT}}$	Model	36.91	376.24	0.0001*
	A	-11.05	232.68	0.0001*
	B	-25.99	1287.55	0.0001*
	A^2	4.66	19.05	0.0033*
	B^2	16.01	224.85	0.0001*
	AB	3.70	17.35	0.0042*
	R^2	0.9936		
Yield of Tar $Y_{t_{OPT}}$	Model	31.22	169.53	0.0001*
	A	0.78	2.10	0.1905
	B	13.18	512.42	0.0001*
	A^2	0.35	0.19	0.6738
	B^2	-11.05	193.97	0.0001*
	AB	-6.96	111.44	0.0001*
	R^2	0.9860		
Yield of Gas $Y_{g_{OPT}}$	Model	31.94	56.22	0.0001*
	A	10.44	89.10	0.0001*
	B	13.81	156.04	0.0001*
	A^2	-4.75	8.50	0.0225*
	B^2	-5.20	10.20	0.0152*
	AB	3.26	5.80	0.0468*
	R^2	0.9583		

* Significant at $p<0.05$ level

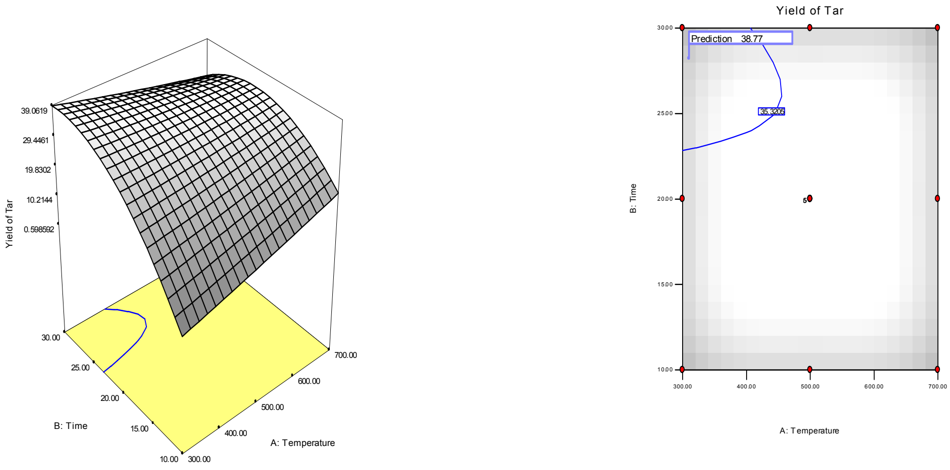
Table 5: Analysis of Variance (ANOVA) for the Responses

Responses	Source of Variance	Degree of Freedom	Sum of Squares	Mean Square	F	Adjusted R^2
$Y_{C_{OPT}}$	Regression	5	5923.13	1184.63	376.24	0.9936
	Residual	7	22.04	3.15		
	Total	12	5945.17			
	Lack of fit	3	22.04	7.35		
$Y_{t_{OPT}}$	Regression	5	1472.81	294.56	169.53	0.9860
	Residual	7	12.16	1.74		
	Total	12	1484.97			
	Lack of fit	3	12.16	4.05		
$Y_{g_{OPT}}$	Regression	5	2061.97	412.39	56.22	0.9583
	Residual	7	51.35	7.34		
	Total	12	2113.32			
	Lack of fit	3	51.35	17.12		



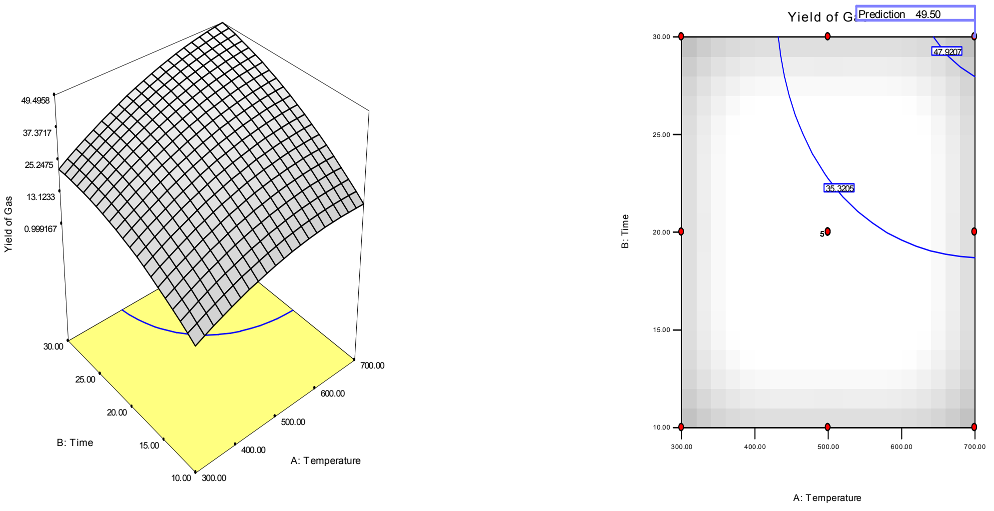
(a) (b)

Figure 1: (a) Response Surface Cubic Plot showing the 3D Effects of Temperature, Time and their Interaction on the Optimum Char yield from OPT. (b) Contour Plot of Figure 1a.



(a) (b)

Figure 2 (a) Response Surface Cubic Plot showing the Effects of Temperature, Time and their Interaction on the Optimum Tar yield from OPT. (b) Contour Plot of Figure 2a.



(a) (b)

Figure 3: (a) Response Surface Cubic Plot showing the Effects of Temperature, Time and their Interaction on the Optimum Gas yield from OPT. (b) Contour Plot of Figure 3a.

4.0 Conclusion

This study has clearly shown the applicability of response surface methodology in selecting pyrolysis parameters that maximises product yields from OPT. This approach has not only resulted in the maximum product yields, but has also shown that OPT can be readily pyrolised into gas, tar (mixture of pyrolitic oil and pyroligneous acid) and char. Pyrolysis of OPT gave the optimum char yield of 98.11% at 300.14ºC, optimum tar yield of 38.77wt% at 310ºC and optimum gas yield of 49.50wt% at 700ºC.

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