Research Article

Optimization of Liquid Fuel Production from Microwave Pyrolysis of Used Tyres

Ronald k. Bett [1,2] **Anil Kumar** [3] **and Zachary O. Siagi** [1]

[1]*Department of Mechanical, Production and Energy Engineering, School of Engineering, Moi University, Uasin Gishu County, P. O Box 3900-30100 Eldoret, Kenya*
[2]*Africa Centre of Excellence II in Phytochemicals, Textiles and Renewable Energy (ACE II PTRE), Moi University, Uasin Gishu County, P. O Box 3900-30100 Eldoret, Kenya*
[3]*Department of Chemical & Process Engineering, School of Engineering, Moi University, Uasin Gishu County, P. O Box 3900-30100 Eldoret, Kenya*

Correspondence should be addressed to Ronald k. Bett; kipkemoironald@gmail.com

Used tyres pose a threat to the environment, especially in developing countries, since the current disposal methods lead to environmental pollution. Pyrolysis liquid from used tyres can be used as a source of fuel to replace petroleum diesel. Microwave pyrolysis is an alternative valorization process that is supposed to save energy and, therefore, is environment friendly. In the current study, microwave pyrolysis was used to produce liquid fuel. Processing variable levels for microwave were power levels of 20, 30, 40, 50, 60, 80, and 100%; the reaction times were 8, 13, 18, 23, and 28 minutes; and the particle sizes were 25, 50, 100, and 200 mm^2. Design-Expert 13 was used for data analysis and optimization, and GC-MS was used for chemical composition analysis, while physiochemical properties were tested using standard methods. Response surface methodology (RSM) was used to study the effects of operating variables and identify the points of optimal yields. For microwave pyrolysis, the highest liquid yield of 39.1 wt. % was at 50% power, 18 min reaction time, and particle size of 25 mm^2. The yield decreased as the particle size increased. RSM gave conditions for optima in agreement with the experimental results. The calorific value for liquid fuel was 48.99 MJ/kg. GC-MS analysis showed that the oil comprised complex mixtures of organic compounds with limonene, toluene, and xylene as major components. The liquid fuel properties meet the required international standards and can be used as an alternative to diesel fuel.

1. Introduction

The major source of tyres in Kenya is tyre imports. According to Dilewski [1], about 62% of all tyres in Kenya are imported. 20% of the tyres in Kenya are those that are imported with cars while those produced in Kenya and the grey market account for 18%. The tyres from grey markets are those that are recycled by retreading. The quantities of tyres from grey markets are obtained by subtracting all tyre imports, tyres that were imported with cars, and those manufactured locally from the total inventory of tyres in Kenya. The quantities of used tyres are expected to increase exponentially. This is due to the fact that the number of people

and companies that buy new cars is increasing [1]. In 2012, the total tonnes per annum of used tyres in Kenya were estimated at 51,000 tons/a and are expected to increase to about 133,000 tons/a in 2031 as shown in Figure 1. According to Mamun et al. [2], tyre pyrolysis oil has a calorific value greater than that of gasoline and petroleum diesel. This implies that it has the potential to be used as a substitute or a blend with petroleum diesel in internal combustion engines [3]. Most tyres are made of isobutylene-isoprene copolymer rubber, styrene-butadiene copolymer rubber (SBR), and *cis*-polybutadiene rubber (CBR). Such rubbers have long chained polymers bonded to sulphur atoms, therefore making the elastomer very stable, hence limiting their degradability [4].
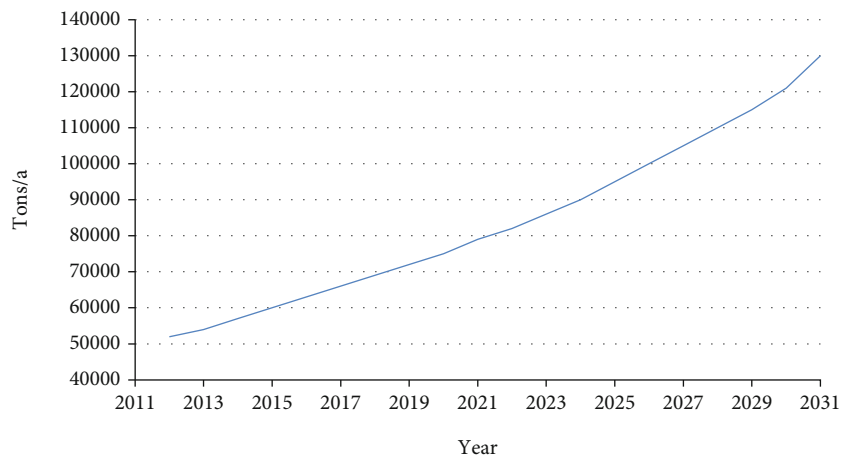
Figure 1: Forecasted quantities of waste tyres in Kenya [1].

Apart from the synthetic rubber, tyres contain carbon black, plasticizers, antioxidants, lubricants, natural rubber, and some inorganic materials such as silica that makes their disposal very complicated. Therefore, due to the difficulty in disposal of used tyres, there is a lot of interest in waste to energy conversion using relevant technologies such as thermochemical conversion. Pyrolysis is one of such processes which involve the thermal cracking of tyre material at elevated temperatures in the absence of oxygen to produce liquid, solid, and gas products [5]. Microwave pyrolysis is one of the latest technologies to replace the conventional heating. It is not only faster but also a cleaner production that leads to reduced energy consumption [6]. The increased use of automobile usage, especially in areas with higher population, has led to environmental problems, one of them being disposal of waste tires [7]. There are several wastes that are being generated every year, and some of them being effectively collected and recovered to be used as a source of energy or chemical feedstock. However, some of the wastes such as used tyres are discarded or burned in ways that can easily pollute the environment. Improper disposal of tyres can result in environmental hazards. This is because tyres have undesirable species which includes soot, heavy metals, and polycyclic aromatic hydrocarbons (PAH). The associated environmental hazards with tyres are due to the fact that they are nonbiodegradable and therefore last for many years. Because of the difficulties that are associated with the contaminants present in the tyres, most of them are disposed by land filling.

The common method used to dispose such wastes (land filling) has no recovery of the potential value of the tyres. Researches have been done on the possible values of pyrooil from thermal pyrolysis, and it has been found out that the pyro oil has several benefits [3]. Pyrolysis is a technique that has been developed to be used as an alternative to convert the wastes to a potential energy sources. The pyrolysis has the potential to recover the energy and chemical value of the used tyres since it generates potentially valuable products from the pyrolysis process.

The energy content of the oil and gaseous products has to be analysed, and the char produced has the potential of being used as a substitute for carbon black. The oil and gaseous products are of great interest because of their potential of being used as a fuel for cooking and can be used in internal combustion engines. Besides, it can be used as a blend for diesel at the right proportions and be used for cooking.

Microwave pyrolysis is a relatively new process which is not only efficient but also has minimum emissions released to the atmosphere [8]. It is characterized by a unique heating technique where the heating effect arises from the interaction of electromagnetic waves together with dipoles within the complex structure of the material. This mode of heating ensures that heat is generated within the material instead of external sources. This ensures that there is a more efficient heating process compared to conventional surface heating. Such heating ensures that there is an even distribution of heat and easier control of the heating process [8]. The aim of the current study is to optimize the liquid fuel yield from microwave pyrolysis by varying microwave power, reaction time, and particle sizes.

2. Materials and Methods

2.1. Feedstock Preparation. The used tyre (Triangle 1000 R 20 10.00X20 Truck Tyre) was used for the preparation of feedstock (tyre chips). It was shredded by a knife to achieve the required size unit of measure being the cross-sectional area. All sizes had a uniform thickness of 2 mm. The feedstock was then screened to remove impurities and dust that were on the surface of the tyre material. They were then dried in the air to remove the moisture that could interfere with the pyrolysis process. To avoid the presence of water in the liquid fuel, low-power microwave pretreatment is recommended. Preheating to about 100°C vaporizes all the moisture present in the tyre chips. The feedstock was then ready for pyrolysis.

2.1.1. Effect of Operating Variables on Microwave Pyrolysis. The effects of operating variables were studied on the process. The variables considered were microwave power, reaction time, and particle size.

2.1.2. Microwave Power. The selected microwave (SAMSUNG GE0103MB1) had an output power of 900 W and a
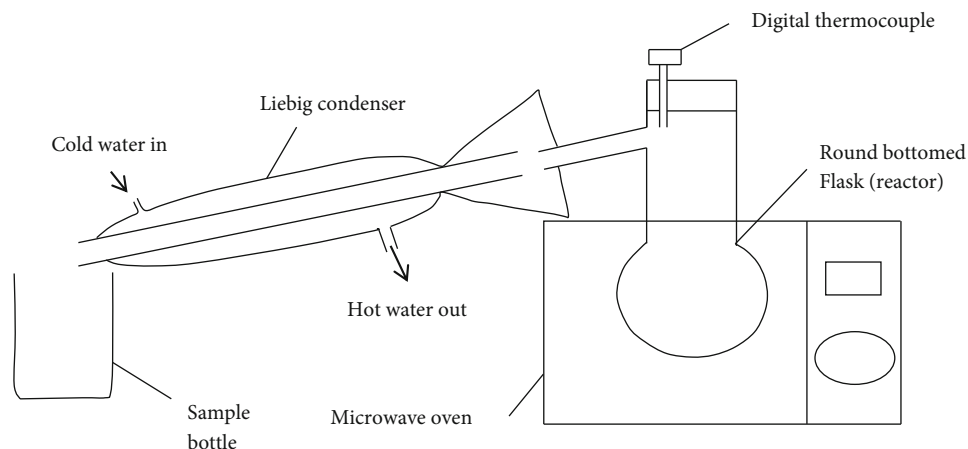
FIGURE 2: Microwave pyrolysis set up.

frequency of 2450 MHz with 10 power levels ranging from 10% (90 W) to 100% (900 W). The other variables were held constant and microwave power varied. The particle size used was 25 mm^2 and a reaction time of 25 minutes. For this experiment, the microwave powers selected were 20%, 30%, 40%, 50%, 60%, 80%, and 100%. Due to the increased pressure and temperatures within the reactor as the microwave heating continues, the condensable products are forced out of the reactor through the sprout of the round bottomed flask. The sprout is connected to a Liebig condenser as illustrated in Figure 2. The Liebig condenser is connected to circulating water at an average temperature of 10°C. A temperature gradient exists between the circulating cold water and the vapour from the reactor. As a result, heat transfer occurs and the temperature of the hot vapour is reduced resulting in condensation. The condensed liquid product is collected.

2.1.3. Reaction Time. The selected microwave has an automated timing system and stops when the set time elapses. The microwave power was set at 100%, and the particle size used was 25 mm^2. The first step was to determine the time taken for the condensable products to condense at full power. The products were then monitored after every 5 minutes.

2.1.4. Particle Size. The sizes used in this experiment were cubic with a uniform thickness of 2 mm. The cross-sectional area of various sizes was varied for investigating the effect of particle size of the feedstock on the yield of microwave pyrolysis process. The cross-sectional areas considered were 25 mm^2, 50 mm^2, 100 mm^2, and 200 mm^2. A microwave power of 100% and reaction time of 25 minutes was used in all sizes for uniformity. 100 grams of each size was placed in the reactor, and the microwave was started.

2.2. Characterization of Liquid Products for Fuel. The physiochemical properties of the liquid fuel was done using standard methods and then compared with published literature. GC-MS analysis was also used to identify the key components in the liquid products.

TABLE 1: Independent variables and their levels in CCD.

Factors	Units	-α=	-1	0	+1	+α
Microwave power (X1)	%	30	40	50	60	70
Reaction time (X2)	mins	10	13	17.5	22	25
Particle size (X3)	mm^2	25	60	112.5	165	200

2.3. Experimental Set-Up. An experimental investigation was done on the pyrolysis of tyre using a microwave oven (SAMSUNG GE0103MB1) with an output power of 900 W and 2450 MHz. Modification was done with the microwave to suit the pyrolysis process. A 50 mm hole was drilled at the ceiling of the microwave to hold the neck of the conical flask. Besides, the hole was meant to ensure that the mouth of the conical flask was out of the microwave cavity. The mouth of the conical flask was then sealed using a wooden cork. The sprout of the conical flask was connected to the Liebig condenser. The 500 mL quartz glass round bottomed flask was utilized as a reactor. 100 g of used tyre is fed into the reactor. The reaction time and microwave power are set, and the microwave is switched on. The feedstock is heated continuously in the absence of oxygen to produce fumes. Due to the pressure build-up in the reactor, the fumes escape through the sprout of the conical flask which is connected to a Liebig condenser as shown in Figure 2. The liquid fuel condenses and is collected in a sample bottle while the gaseous products escape. The solid residue remains in the round-bottomed flask.

2.4. ANOVA and Regression Analysis. A central composite design (CCD) was used with five levels, and three factors were used for this analysis. The three variables, particle size, microwave power, and reaction time were optimized using the CCD. The central values, step sizes, and the range of variables were as follows: central microwave power of 50%, step of 10%, and range of 40%-60%; central reaction time of 17.5 minutes, step of 4.5 minutes, and range of 13 minutes to 22 minutes; and central particle size of 112.5 mm^2, step of 52.5 mm^2, and range of 60 mm^2–165 mm^2 as shown in Table 1 below.
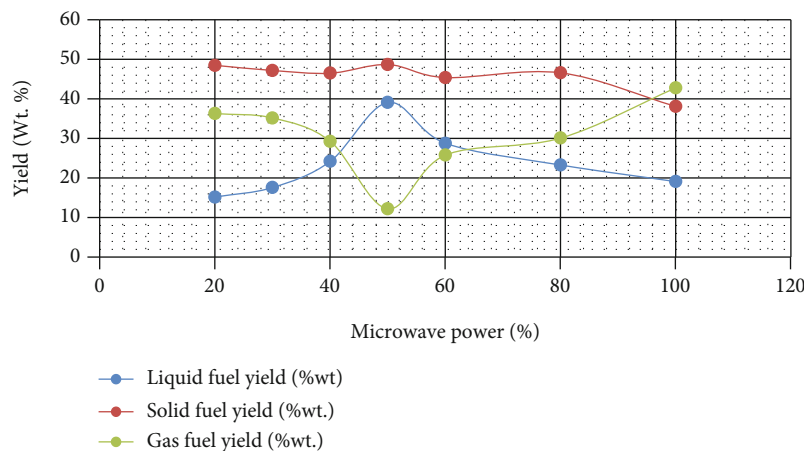
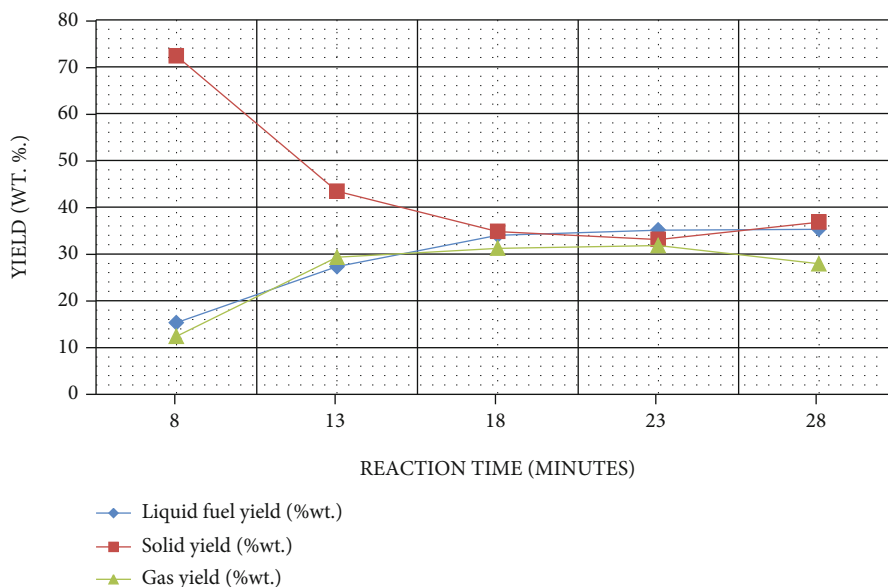Figure 3: Effect of microwave power on liquid, solid, and gas yield.

Figure 4: Effect of reaction time on yield.

The number of experimental obtained at each number of factors is given by the formula, $N = 2^n + 2(n) + n_c$, where N is the number of runs, n is the number of factors, and n_c is the number of replications at the centre points. A total of 15 experiments for a single replication were obtained. Considering 3 replications of the experiments, a total of 45 runs were obtained. For a full factorial rotatable design, $\alpha = [2^k]^{1/4} = [2^3]^{1/4} = 1.682$ [9]. 0_1, 0_2, and 0_3 are the centre points while $-\alpha\,(1.682)$ and $+\alpha\,(1.682)$ are the axial points. To get the value of the axial point, the following equation is applied: Axial point = mean of both the upper and lower level $\pm\,\alpha$ (range between the upper and lower level divided by 2) [9]. Therefore, axial point $= X \pm \alpha\,(\text{Range}/2)$; $N = (2^n + 2(n) + n_c) \times 3 = (2^3 + 2(3) + 1) \times 3 = 45$ runs. A full quadratic model for liquid fuel yield was tested and Design-Expert 13 trial version was used for ANOVA and regression analysis.

3. Results and Discussion

3.1. Effect of Microwave Power. Microwave power (MP) was varied from 20% to 100% for a microwave with a power output of 900 watts each run for 30 minutes using a particle size of 25 mm^2. The results indicated an increase in liquid fuel yield from 15.2 (wt. %) at a microwave power of 20% to an optimum point at 50% microwave power with a yield of 39.1 (wt. %). Then, there is a continuous decrease in the liquid fuel yield to 19.1 (wt. %) at 100% microwave power. The solid char indicated a uniformly declining trend from 48.5 (wt. %) at 20% MP to 46.5 (wt. %). There was a slight increase to an optimum value of 48.7 (wt. %) at 50% MP and then a continuous uniform decline to 38.1 (wt. %) at 100% MP. Finally, the gas yield indicated a declining trend from 36.3 (wt. %) at 20% MP to the lowest yield of 12.2 (wt. %) at 50% MP as indicated in Figure 3. There was an increasing trend with a maximum yield of 42.8 (wt. %) at 100% MP.
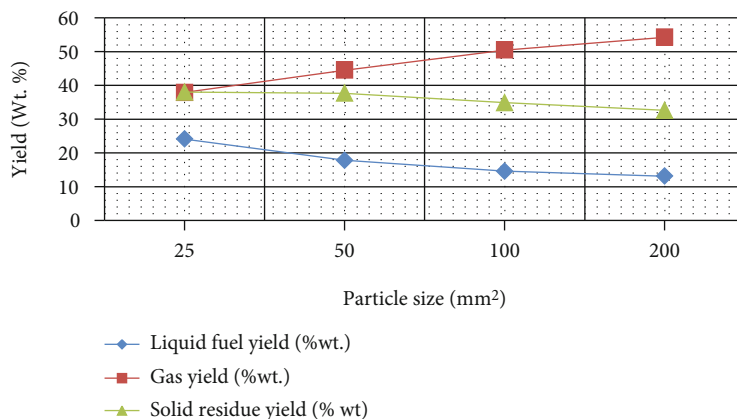
FIGURE 5: Effect of particle size on yield.

The trend of the results is in agreement with the published literature [10]. The rise of the liquid yield at MP of 20% to 50% is as a result of temperature elevation at higher MPs leading to higher oily products. When the MP was further increased from 50% to 100%, there was a declining trend as a result of extremely higher temperatures leading to cracking of oil molecules into lighter gaseous molecules. This fact also substantiated the fact that there was a continuous increase in gaseous products from MP of 50% to 100%. The trend of solid residue was dictated by the trends of gaseous and liquid products.

The mass of the products was obtained using a weighing scale. The initial mass of the feedstock was weighed and recorded as M_1. The mass of the liquid products obtained were weighed and recorded as M_2. The mass of the solid residue was also weighed and recorded as M_3. Therefore, mass of gaseous products in accordance with the law of conservation of mass is $\{M_1 - (M_2 + M_3)\}$.

3.2. Effect of Reaction Time on Yield.

The selected MP for the runs to investigate reaction time was constant at 50%. The sample size for all runs was 100 grams of $25\,mm^2$. The times considered were 8 min, 13 min, 18 min, 23 mins, and 28 min. There was an increase in the liquid fuel yield from 8 min to 19 min from 15.3 (wt. %) to 35.0 (wt. %), respectively. Beyond 19 min, there was no further increase in liquid fuel yield as the curve flattens as shown in Figure 4. Similarly, there was an increase in the gas yield from 12.4 (wt. %) to 31.5 (wt. %) from 8 min to 20 mins, respectively. Beyond 20 min, there was no further increase in gas yield as indicated in Figure 4. The solid products declined from 72.3 (wt. %) to 35.0 (wt. %) from 8 min to 20 mins, respectively; then, the yield became constant beyond 20 min. The trend for liquid fuel production over time was in agreement with the published literature [11]. The increasing trend in liquid fuel and gas production from 8 min to about 18 minutes is because the feedstock is allowed more time for the pyrolysis process to occur. At about 18 minutes, the pyrolysis process is complete and all products from the feedstock have been cracked leading to no more production of liquid and gaseous products.

3.3. Effect of Particle Size on Yield.

The particle sizes considered were $25\,mm^2$, $50\,mm^2$, $100\,mm^2$, and $200\,mm^2$, and the sample size was 100 grams each subjected for 30 min. On the other hand, the MP was kept constant at 100%. The results as shown in Figure 5 indicated that there was a continuous decline in liquid fuel yield from 24.1 (wt. %) to 13.1 (wt. %) for particle sizes of between $25\,mm^2$ and $200\,mm^2$, respectively. On the other hand, the gas products depicted a uniform increasing trend from 37.9 (wt. %) to 54.3 (wt. %) for particle sizes between $25\,mm^2$ and $200\,mm^2$, respectively. The solid residue was dictated by the yield of liquid and gaseous products. The decrease in liquid fuel is as a result of reduced exposed surface area for further cracking. The increase in gaseous products with the increase in particle size is as a result of incomplete cracking of tyre particles to form liquid fuel. Most of the components escape as gases, hence the trend.

3.4. Process Optimization.

Table 2 illustrates the CCD matrix with experimental and predicted yields after analysis using the design expert.

Table 3 gives the ANOVA for regression analysis for a full quadratic model. The full quadratic model is the quadratic equation that relates the liquid fuel yield for microwave pyrolysis of used tyres as a function of the variables. The specific variables for this experiment are microwave power, reaction time, and particle size. The model is illustrated in Equation (1).

As illustrated in Table 3, the model F-value of 102633.49 implies that the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

p values less than 0.0500 indicate model terms are significant. In this case, X1, X2, X3, X1.X2, X2.X3, X1.X3, $(X1)^2$, $(X2)^2$, and $(X3)^2$ are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The lack-of-fit F-value of 1.27 implies the lack-of-fit is not significant relative to the pure error. There is a 30.28% chance that a lack-of-fit F-value this large could occur due to noise. The p value for lack-of-fit was greater than 0.05, and therefore, it was not significant.

TABLE 2: CCD matrix with experimental and predicted yields.

Std	Run	X1 : microwave power (%)	X2 : reaction time (mins)	X3 : particle size (mm^2)	Exp. yield (wt. %)	Predicted yield (wt. %)	Residual
12	1	60	22	60	35	35.02	-0.0158
39	2	50	17.5	25	37	37.02	-0.0244
24	3	60	22	165	30	30.01	-0.0117
5	4	60	13	60	29.2	29.17	0.0312
26	5	30	17.5	112.5	27	27.01	-0.0056
30	6	70	17.5	112.5	28.4	28.39	0.0111
42	7	50	17.5	200	32.1	32.1	-0.0009
15	8	40	13	165	26.6	26.59	0.0103
8	9	40	22	60	35.1	35.11	-0.0075
41	10	50	17.5	200	32.1	32.1	-0.0009
34	11	50	25	112.5	31.2	31.18	0.0204
44	12	50	17.5	112.5	35.4	35.4	0.0007
17	13	60	13	165	28.1	28.06	0.0353
35	14	50	25	112.5	31.2	31.18	0.0204
40	15	50	17.5	200	32.1	32.1	-0.0009
3	16	40	13	60	27.5	27.49	0.0062
29	17	70	17.5	112.5	28.4	28.39	0.0111
7	18	40	22	60	35.1	35.11	-0.0075
4	19	60	13	60	29.1	29.17	-0.0688
16	20	60	13	165	28	28.06	-0.0647
2	21	40	13	60	27.5	27.49	0.0062
27	22	30	17.5	112.5	27	27.01	-0.0056
43	23	50	17.5	112.5	35.4	35.4	0.0007
33	24	50	10	112.5	23.2	23.21	-0.0124
37	25	50	17.5	25	37.1	37.02	0.0756
31	26	50	10	112.5	23.2	23.21	-0.0124
32	27	50	10	112.5	23.2	23.21	-0.0124
20	28	40	22	165	30.3	30.3	-0.0034
10	29	60	22	60	35	35.02	-0.0158
21	30	40	22	165	30.3	30.3	-0.0034
36	31	50	25	112.5	31.2	31.18	0.0204
9	32	40	22	60	35.1	35.11	-0.0075
19	33	40	22	165	30.3	30.3	-0.0034
45	34	50	17.5	112.5	35.4	35.4	0.0007
18	35	60	13	165	28.1	28.06	0.0353
11	36	60	22	60	35	35.02	-0.0158
22	37	60	22	165	30	30.01	-0.0117
6	38	60	13	60	29.2	29.17	0.0312
23	39	60	22	165	30	30.01	-0.0117
38	40	50	17.5	25	37	37.02	-0.0244
25	41	30	17.5	112.5	27	27.01	-0.0056
28	42	70	17.5	112.5	28.4	28.39	0.0111
14	43	40	13	165	26.6	26.59	0.0103
13	44	40	13	165	26.6	26.59	0.0103
1	45	40	13	60	27.5	27.49	0.0062

TABLE 3: ANOVA for response surface quadratic model.

| Source	Sum of squares	df	Mean square	F-value	p value	
Model	639.49	9	71.05	1.03E+05	<0.0001	Significant
X1-microwave power	5.74	1	5.74	8292.19	<0.0001	
X2-reaction time	232.32	1	232.32	3.36E+05	<0.0001	
X3-particle size	88.72	1	88.72	1.28E+05	<0.0001	
X1.X2	4.68	1	4.68	6762.31	<0.0001	
X1.X3	0.06	1	0.06	86.67	<0.0001	
X2.X3	22.82	1	22.82	32954.52	<0.0001	
$(X1)^2$	121.19	1	121.19	1.75E+05	<0.0001	
$(X2)^2$	142.02	1	142.02	2.05E+05	<0.0001	
$(X3)^2$	1.48	1	1.48	2133.74	<0.0001	
Residual	0.0242	35	0.0007			
Lack-of-fit	0.0042	5	0.0008	1.27	0.3028	Not significant
Pure error	0.02	30	0.0007			
Cor total	639.52	44				
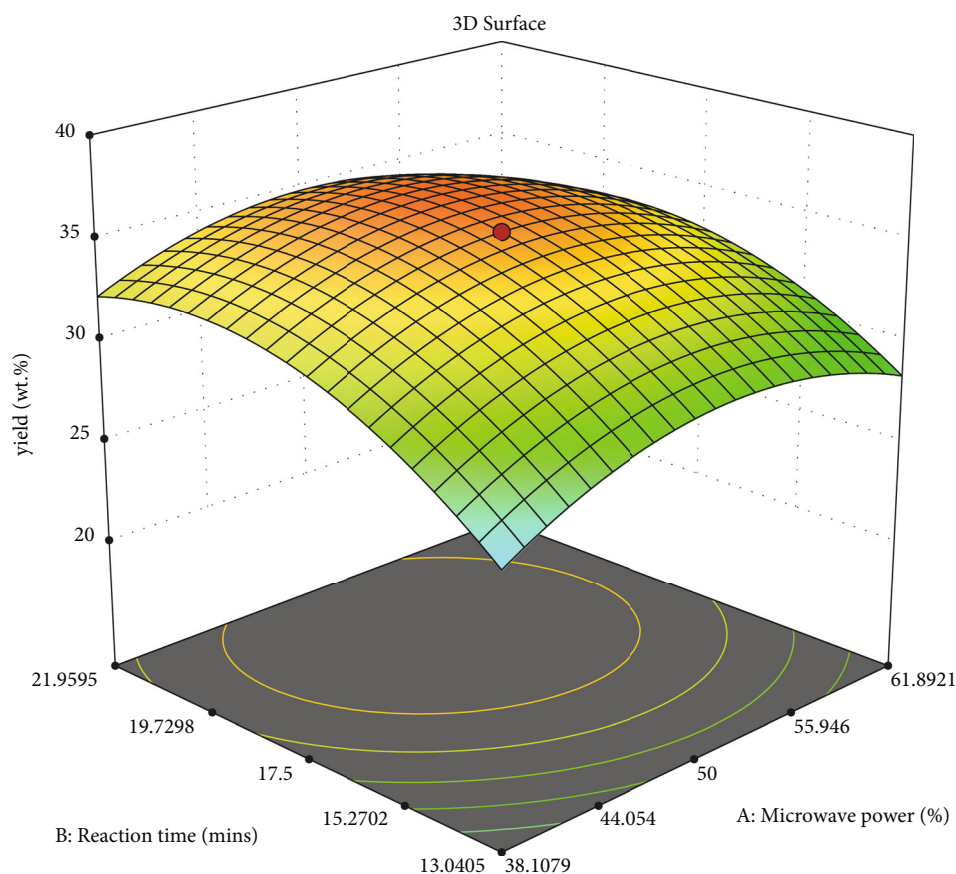
FIGURE 6: RSM plot for the effect of microwave power and reaction time on yield.

The full quadratic model is given by

$$
\begin{aligned}
\text{Yield}\,(Y) = {} & -83.89211 + 2.14258\,X1 + 6.59046\,X2 + 0.073437\,X3 \\
& - 0.009815\,X1.X2 - 0.000095\,X1.X3 - 0.004127\,X2.X3 \\
& - 0.019255\,(X1)2 - 0.145837\,(X2)2 \\
& - 0.000109(X3).
\end{aligned}
\tag{1}
$$

3.4.1. Response Surface Plots. Equation (1) was used to plot the response surface and contours for the optimization of liquid fuel yield. Figure 6 is a plot of yield as a function of microwave power and reaction time. The optima lie close to a microwave power of 50% and a reaction time of 17.5 minutes.

Figure 7 gives a plot for yield as a function of microwave power and particle size. The optima lie close to a microwave power of 50% and particle size of 25 mm^2.
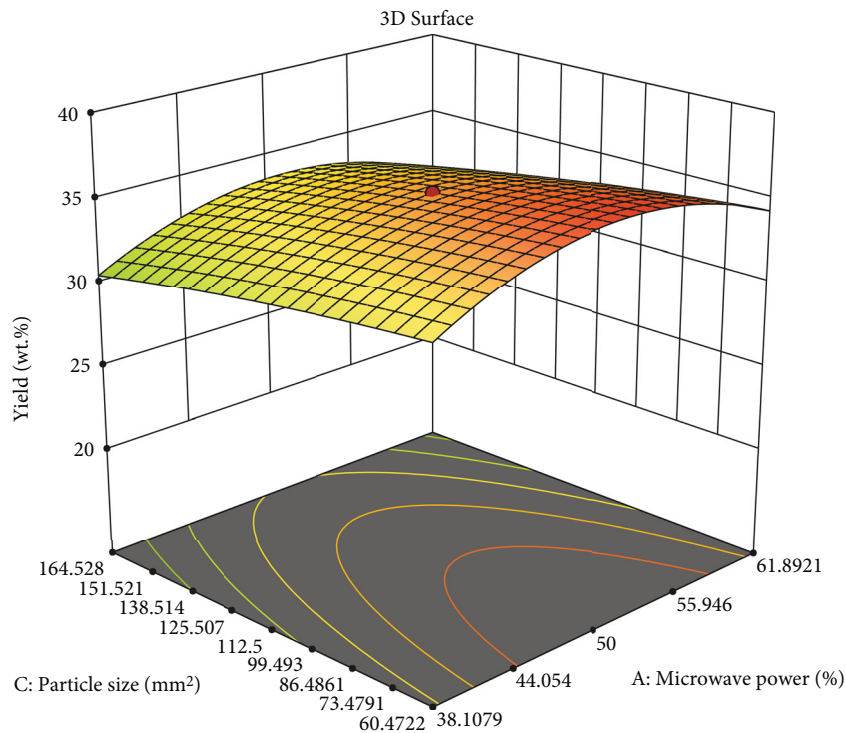
Figure 7: RSM plot for the effect of microwave power and particle size on yield.
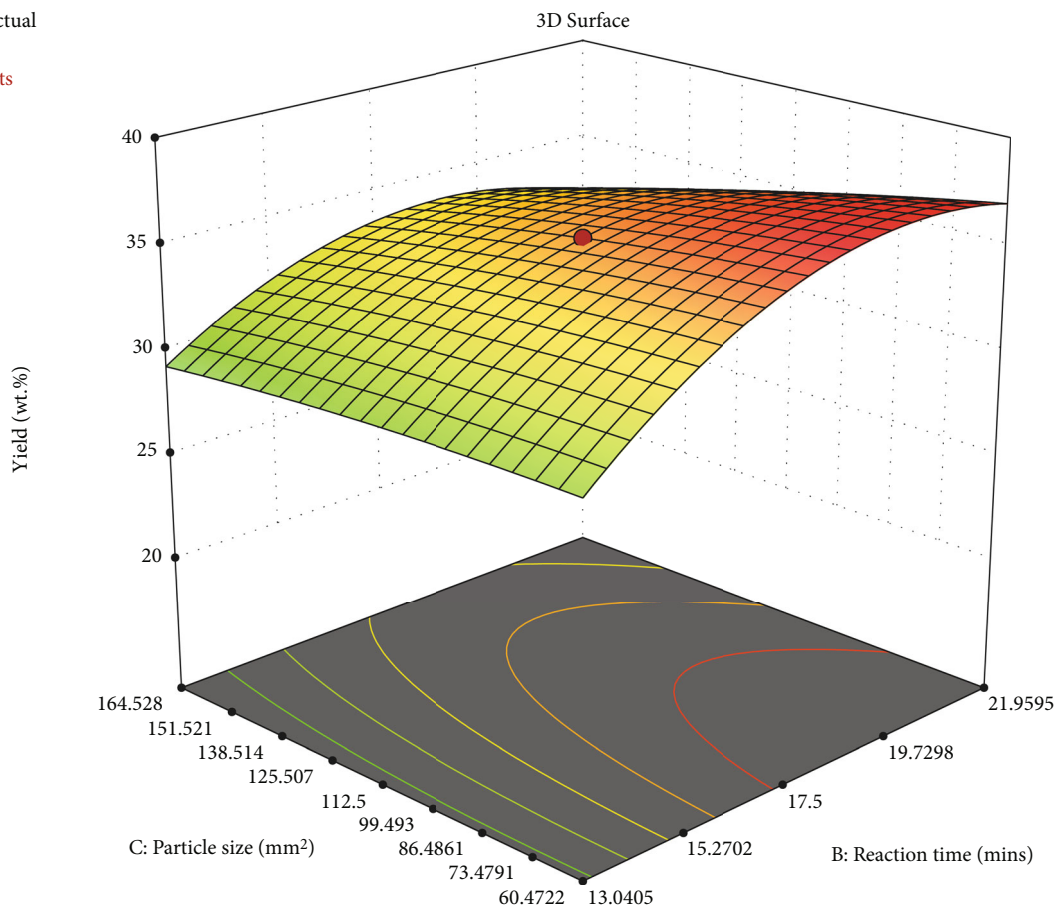

Figure 8: RSM plot for the effect of particle size and reaction time on yield.

TABLE 4: Physiochemical properties of tyre pyrolysis oil (TPO) compared to commercial diesel, WTPO, and WPPO according to Hariram et al. [12].

Properties	Units	Commercial diesel	WTPO	WPPO	Testing methods for diesel, WTPO, & WPPO	TPO	Testing method for TPO
Gross calorific value	MJ/kg	43.9	42.7	39.45	IS:1448 P:6	48.99	ASTM D2015
Kinematic viscosity, @ 40°C	cSt	2.1	3.4	2.2	IS:1448 P:25	3.07	AOAC
Flash point	°C	5 2	4 6	4 4	IS:1448 P:20	61	ASTM D2015
Fire point	°C	5 7	5 3	4 7	IS:1448 P:20	65	ASTM D2015
Density @ 15°C	kg/m^3	832	936	837.5	IS:1448 P:16	910	AOAC
Cetane index	—	46.4	5 5	6 8	IS:1448 P:9	—	—
Carbon residue	%	0.37	2.21	72.79	IS:1448 P:122	0.75	ASTM D2015
Sulphur content	%	0.047	0.99	0.034	IS:1448 P:33	0.08	AOAC
Ash content	%	0.01	0.33	0.0003	IS:1448 P:126	1.9	AOAC

TABLE 5: GC analysis of optimal liquid fuel for microwave pyrolysis.

Retention time (RT) (mins)	Components	Molecular formula	Peak area %
13.46	D-Limonene	$C_{10}H_{16}$	20.23
7.03	Toluene	C_7H_8	10.65
8.82	m-Xylene	C_8H_{10}	7.31
27.09	1-Methylnaphthalene	$C_{11}H_{10}$	5.8
15.59	Naphthalene	$C_{10}H_8$	5.42
28.88	Estradiol, 3-deoxy	$C_{18}H_{24}O$	3.5
15.72	3,4-Dihydro-1-methylnaphthalene	$C_{11}H_{12}$	2.74
25.09	Naphthalene,2,7 –dimethyl	$C_{12}H_{12}$	2.5
20	Naphthalene 1,7-dimethyl	$C_{12}H_{12}$	1.96
11.33	o-Xylene	C_8H_{10}	1.4
19.44	Naphthalene, 1,2-dihydro	$C_{10}H_{10}$	1.2
12.64	Cyclohexane, 1-methyl-5-(1-methylethenyl)-(R)	$C_{10}H_{16}$	1.1
5.62	Benzene	C_6H_6	0.92
4.94	Ethylenzene	C_8H_8	0.6
30.33	Fluoranthene	$C_{16}H_{10}$	0.45
7.96	2,4-Dimethyl-quinolin	$C_{11}H_{11}N$	0.41

Figure 8 gives a plot for yield as a function of particle size and reaction time. The optima lie close to a particle size of 25 mm^2 and reaction time of 17.5 minutes.

3.5. Characterization of Liquid Products for Fuel. The tests that were done on tyre pyrolysis oil (TPO) are the physiochemical properties and GC-MS analysis.

3.5.1. Physiochemical Properties. Table 4 summarizes the results of the physiochemical properties tests for tyre pyrolysis oil compared to the results of published literature done by Hariram et al. [12]. The research by Hariram et al. compares properties of waste tyre pyrolysis oil (WTPO), waste plastic pyrolysis oil (WPPO), and that of commercial diesel.

From the results indicated in Table 4, most of the parameters are close to that of commercial diesel. The gross calorific value of TPO is at 48.99 MJ/kg while that obtained by Hariram et al. [12] for WTPO was at 42.7 MJ/kg. The gross calorific value of commercial diesel is between 42 and

46 MJ/kg according to the World Nuclear Association [13] and 43.9 MJ/kg according to Hariram et al. [12]. This implies that the TPO has a calorific value higher than that of commercial diesel. Other parameters such as flash point, fire point, density, and viscosity are close to that of petroleum diesel. Upon further purification, TPO can be used directly in internal combustion engines instead of diesel. The calorific value of heavy fuel oil (HFO) is at 41 MJ/kg according to total Kenya [14]. The required standards for HFO sold in Kenya according to total Kenya [14] is that it must meet the following critical parameters: maximum kinematic viscosity @ 500C of 180 cst, sulphur content of 2.3% maximum, and a minimum net calorific value of 41 MJ/kg. Therefore, TPO qualifies to be used directly as an HFO.

3.5.2. GC-MS Analysis. The results of GC analysis are as illustrated in Table 5. From the analysis, it is evidenced that the TPO comprises of a complex mixture of hydrocarbons with the major components being limonene, toluene, and xylene.

The proportions of the tested components are as illustrated in Table 5. The results are in agreement with the published literature by FLaresgoiti et al. [15]. According to FLaresgoiti et al., the tyre pyrolysis oil comprises of a complex mixture of C6–C24 organic compounds. The oil comprises of polycyclic aromatics in various proportions such as phenanthrenes, diphenyl, naphthalenes, and fluorenes. Besides, light hydrocarbons such as toluene, limonene, and xylene are present at various proportions [15]. Most of the detected components are similar to those in commercial diesel fuel according to Liang et al. [16]. Therefore, the tyre pyrolysis oil qualifies to be used as a fuel.

4. Conclusion and Recommendations

In this study, the optimization of liquid fuel yield was carried out using microwave pyrolysis technique. The liquid fuel yield was correlated to a quadratic equation expressed as a function of reaction variables. ANOVA indicated that the correlations fitted the experimental data satisfactorily. Response surface and contour plots indicated that the highest yield of 38.4% (wt. %) corresponded to a microwave power of 50%, particle size of $25\,mm^2$, and a reaction time of 17.5 minutes. In the published literature, a similar trend is observed for the effect of microwave power on the yield. This is because at 50% power level, the oily products are cracked sufficiently because of sufficient temperature. At lower power levels, the temperatures are lower and all complex components may not be cracked to form oily products. On the other hand, at higher power levels, the temperatures will be elevated further and the oily products formed may further be cracked to form gaseous products, thus reducing the liquid products. The particle size of $25\,mm^2$ was the smallest particle size used and gave the highest liquid fuel yield when interactions with other variables are held constant. The possible reason is the increased surface area for the microwave heating, and this indicates clearly that even a smaller particle size could give better results. The reaction time of 17.5 minutes was the optimal time that allowed the pyrolysis process to be completed beyond which no more increase in the liquid fuel yield. At other optimal conditions, it is the optimal time for a 100 grams sample of tyres to produce liquid fuel. The physiochemical properties of the TPO as indicated in Table 4 are close to those of petroleum diesel and can therefore be used as an alternative source of fuel. The GC-MS analysis on liquid fuel indicated that they comprise of complex mixtures of organic compounds with larger proportions of limonene, toluene, and xylene.

4.1. Recommendations for Further Research. The liquid fuel produced is not refined despite the fact that it has a higher calorific value compared to petroleum diesel [2]. Research is still needed in refining the liquid fuel to be used directly in internal combustion engines. Furthermore, more research is needed on the composition and possible use of gaseous products and upscaling of the microwave pyrolysis process.

Data Availability

The article contains all the relevant data. The corresponding author would provide any additional data upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

References

[1] G. Dilewski, *Waste Tyre Management Kenya*, StudyLib.net., Nairobi, 2012, https://studylib.net/doc/8747300/content-of-the-presentation—kmi—kenya-motor-industry-.

[2] M. A. Al, B. Salam, F. N. Ani, S. Md, and H. Kabir, *Pyrolysis of scrap tyre by microwave*, Chittagong University of Engineering and Technology, 2015.

[3] S. Murugan, M. C. Ramaswamy, and G. Nagarajan, "The use of tyre pyrolysis oil in diesel engines," *Waste Management*, vol. 28, no. 12, pp. 2743–2749, 2008.

[4] A. Ramirez-Canon, Y. Muñoz-Camelo, and P. Singh, "Decomposition of used tyre rubber by pyrolysis: enhancement of the physical properties of the liquid fraction using a hydrogen stream," *Environments*, vol. 5, no. 6, p. 72, 2018.

[5] Wikipedia, "Pyrolysis n.d," April 2021. https://en.wikipedia.org/wiki/Pyrolysis.

[6] A. Kumar, A. Chirchir, S. S. Namango, and H. K. Kiriamiti, "Microwave irradiated transesterification of croton megalocarpus oil–process optimization using response surface methodology," in *Proceedings of the 2016 Annual Conference on Sustainable Research and Innovation*, pp. 177–184, Kenya School of Monetary Studies, Nairobi, Kenya, 2016.

[7] S. S. Lam and H. A. Chase, "A review on waste to energy processes using microwave pyrolysis," *Energies*, vol. 5, no. 10, pp. 4209–4232, 2012.

[8] A. M. Kalla and R. Devaraju, "Microwave energy and its application in food industry: a reviw," *Asian Journal of Dairy and Food Research*, vol. 36, pp. 37–44, 2017.

[9] J. Antony, *Design of Experiments for Engineers and Scientists*, Elsevier, 2nd ed. edition, 2014.

[10] Z. Song, Y. Yang, J. Sun et al., "Effect of power level on the microwave pyrolysis of tire powder," *Energy*, vol. 127, pp. 571–580, 2017.

[11] C. Rius-Alonso, L. Olivares-Lachica, D. Gallard-Paz et al., "Thermal and microwave pyrolysis of tires to produce fuel," in *Proceedings of EDULEARN11 Conference*, pp. 281–288, Barcelona, Spain, 2011.

[12] V. Hariram, S. Seralathan, and A. M. Raffiq, "Formulation and characterization of pyrolytic oil from waste tyre and waste plastic: a comparative study," *Nature, Environment and Pollution Technology*, vol. 16, pp. 1183–1188, 2017.

[13] World Nuclear Association, "Heat values of various fuels," 2016, https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx.

[14] T. Kenya, "Heavy fuel oil," June 2021. https://www.total.co.ke/corporate-solutions/fuels/heavy-fuel-oil.

[15] M. F. Laresgoiti, B. Caballero, I. de Marco, A. Torres, M. Cabrero, and M. Chomón, "Characterization of the liquid products obtained in tyre pyrolysis," *Journal of Analytical and Applied Pyrolysis*, vol. 71, no. 2, pp. 917–934, 2004.

[16] F. Liang, M. Lu, T. C. Keener, Z. Liu, and S.-J. Khang, "The organic composition of diesel particulate matter, diesel fuel and engine oil of a non-road diesel generator," *Journal of Environmental Monitoring*, vol. 7, no. 10, pp. 983–988, 2005.