Eng. Sci., 2024, **31**, 1211

Engineered Science
DOI: https://dx.doi.org/10.30919/es1211

Optimizing Energy Conversion in Waste Cooking Oil Pyrolysis with a Low-Cost Carbonaceous Catalyst Using Response Surface Methodology

Warintorn Banchapattanasakda,[1] Channarong Asavatesanupap[2,*] and Malee Santikunaporn[1,*]

Abstract

The objective of this study was to determine the optimal conditions for converting waste cooking oil (WCO) into bio-oil via pyrolysis with activated carbon (AC) using response surface methodology (RSM). A central composite design was employed to model the relationship between reaction temperature, AC to WCO ratio, and Brauer-Emmett-Teller (BET) surface area and their effects on bio-oil yield and energy conversion. The analysis of variance identified reaction temperature as the most influential factor. The optimal conditions for maximum energy conversion (93.41%) were found to be a temperature of 425 °C, an AC to WCO ratio of 1:40, and a BET surface area of 758 m^2/g. In contrast, under conditions with a BET surface area of 1000 m^2/g, the energy conversion was 88.14%, which was the highest energy conversion observed in the experiment. Under this condition, the bio-oil contained over 40% diesel-like compounds. However, due to its high acid value, the bio-oil is not directly usable in diesel engines without further treatment.

Keywords: Waste cooking oil; Energy conversion; Pyrolysis; Bio-oil; Response surface methodology.
Received: 23 April 2024; Revised: 11 June 2024; Accepted: 20 June 2024.
Article type: Research article.

1. Introduction

The rising demand for fossil fuels, driven by industrialization, global economic expansion, and population growth, has intensified the search for alternative energy sources. Biofuels have become a promising alternative due to their potential to replace or blend with fossil fuels.[1] Early research primarily focused on first-generation biofuels derived from agricultural residues and industrial byproducts.[2] Subsequent studies expanded to second-generation biofuels, exploring a broader range of feedstocks, including plastics,[3-6] rubber tires,[7] and waste lube oil,[8] as well as conversion techniques like pyrolysis, a thermochemical process. Pyrolysis, which involves heating biomass in the absence of oxygen, produces a variety of products. However, it faces challenges such as relatively low yields and inferior fuel properties compared to fossil fuels, mainly due to the high oxygen content of the resulting products.[8]

Waste cooking oil (WCO) has gained attention as a potential feedstock for biofuel production via pyrolysis due to its abundant availability and economic viability.[9,10] The global annual production of WCO is estimated to account for 20-32% of total edible oil consumption, amounting to 40-50 million tons, with projections to increase to 55-65 million tons by 2025.[11,12] In Thailand, the annual production of WCO is approximately 580,000 tons.[12] However, WCO management in Thailand remains suboptimal due to a lack of proper disposal guidelines, leading to socio-environmental challenges.[13] Currently, only 2.5% of WCO is recycled,[13] highlighting the significant potential for improvement in WCO waste management. Harnessing value from WCO offers a promising solution to the environmental problems associated with its disposal.[14]

Using WCO as direct fuel in diesel engines presents challenges due to inefficient combustion, which leads to increased air pollution from the accumulation of particulate matter.[15,16] Several techniques have been proposed to improve the characteristics of WCO, making it more comparable to diesel fuel. These methods include transesterification, which

---

[1] *Department of Chemical Engineering, Faculty of Engineering, Thammasat School of Engineering, Faculty of Engineering, Thammasat University, Pathum Thani 12120, Thailand.*
[2] *Department of Mechanical Engineering, Faculty of Engineering, Thammasat School of Engineering, Faculty of Engineering, Thammasat University, Pathum Thani 12120, Thailand.*
**Email:* smalee@engr.tu.ac.th (M. Santikunaporn), acharnna@engr.tu.ac.th (C. Asavatesanupap)

converts WCO into a different chemical compound, and thermochemical conversion via pyrolysis, which utilizes the organic molecules in WCO.[16] The temperature, catalysts, and their dosage in pyrolysis significantly influence both the yield and properties of the resulting liquid bio-oil.[17] Although activated carbon (AC) has been widely studied as a catalyst in biomass pyrolysis, its application in WCO pyrolysis remains limited. Some studies have explored its role as an absorber in microwave-assisted pyrolysis.[18,19] The presence of pores in AC increases its reactivity in traditional WCO pyrolysis, making it a promising catalyst. However, this aspect has not been as extensively studied as the use of zeolites or aluminosilicates in WCO catalytic pyrolysis or the use of AC solely as a heat-transferring agent in microwave-assisted pyrolysis.[17,20,21]

In addition to the amount of AC used in WCO pyrolysis, the porosity characteristics and Brunauer-Emmett-Teller (BET) surface area are also crucial factors. These characteristics play a significant role in determining the effectiveness of AC in the WCO pyrolysis process. This study demonstrates the impact of key reaction parameters, such as reaction temperature, AC dose, and BET surface area, on the production of liquid bio-oil. Our focus is not only on the bio-oil yield but also on the percentage of energy conversion. Lam *et al.*[19] investigated the effect of AC dose on both the yield of liquid bio-oil and energy recovery based on the heating value of bio-oil produced from microwave pyrolysis of spent frying oil. The aim of their study was to assess the economic viability of producing liquid bio-oil.

Several optimization tools, including Design Expert, Super Pro Designer, and response surface methodology (RSM), have been used to examine the influence of process parameters on maximizing bio-oil production during pyrolysis using various feedstocks.[22-25] The RSM method is particularly valuable for assessing the relationships between process factors and predicting pyrolytic product yields using mathematical and statistical techniques. This approach enables the identification of optimal conditions for maximizing liquid yields while minimizing the number of required experiments. It also employs analysis of variance (ANOVA) to evaluate the significance and appropriateness of the model provided by the RSM.[26,27] Kadlimatti *et al.* investigated the optimization of bio-oil production from food waste using microwave-assisted pyrolysis with RSM.[28] The optimal pyrolysis conditions, including a temperature of 400 °C, a residence time of 30 minutes, a nitrogen gas flow rate of 50 ml/min, and a microwave power of 450 watts, resulted in a maximum bio-oil yield of 30.24 wt%. Pinto *et al.*[29] studied the optimization of liquid oil production from glycerol, polyethylene waste, and waste tire pyrolysis using RSM. They found that RSM is an effective method for predicting liquid oil yields with minimal experimental effort. Waste tire pyrolysis produced the most favorable results in terms of conversion and liquid yields, reaching 80% and 62 wt%, respectively, when the process was conducted at 450 °C for 60 minutes. Neha and Remya studied the co-pyrolysis of food waste and low-density polyethylene (LDPE) using microwave technology.[30] They employed RSM to determine the optimal operating parameters for maximizing bio-oil output. Their study, which involved 17 experimental runs, found that the highest achievable bio-oil production, while minimizing acidity, was 42 wt% under optimal conditions of 550 °C and a residence time of 7 seconds, with 13 wt% LDPE in the feed. Gupta *et al.* recently studied predicting biofuel production from pine needle pyrolysis using an RSM model.[31,32] The optimal conditions were achieved at a temperature of 552 °C, a heating rate of 50 °C/min, and an inert gas flow rate of 164.40 ml/min, resulting in bio-oil with a maximum yield of 51.11 wt%.

However, there are currently fewer reports on the optimization of carbonaceous catalytic pyrolysis parameters for bio-oil production from WCO using RSM. Optimizing the catalytic pyrolysis conditions of WCO is essential to maximize bio-oil production and enhance energy conversion. The emphasis on energy conversion focuses on the energy derived from the WCO pyrolysis process rather than solely on the quantity of liquid bio-oil produced. Energy conversion is determined by comparing the heating value and yield of liquid bio-oil with the heating value and mass of WCO used as feedstock.[19] Examining various factors and optimizing the operating parameters in the laboratory can facilitate the development of pilot-scale plants, thus supporting the industrial-scale development of pyrolysis reactors. Therefore, the relationship between reaction temperatures (375, 400, and 425 °C), AC:WCO ratios (1:40, 1:30, and 1:20), and the BET surface area of AC (500, 750, and 1000 m^2/g) was statistically estimated and experimentally designed using central composite design (CCD) with RSM, incorporating three factors at three levels.

2. Experimental section

2.1 Materials

WCO was collected from leftover frying palm oil in Samut Sakhon, Thailand. The WCO sample, which had a dark-yellowish color, was stored in aluminum containers at room temperature and used directly in pyrolysis tests without any prior treatment. The catalysts used in this study were AC samples with varying BET surface areas. The first sample, obtained from BioCat CS1100, had a surface area of approximately 750 m^2/g. The second sample, derived from apricot stones, had two different surface areas: approximately 500 and 1000 m^2/g. The apricot stone samples were prepared by carbonizing at 400 °C with a heating rate of 10 °C/min for 1 hour under a nitrogen flow rate of 50 ml/min. The samples were then mixed with potassium hydroxide (KOH) at 80 °C for 2 hours, followed by calcination at 850 °C for 1 hour under nitrogen flow. The resulting AC was then ground and sieved to obtain a particle size range of 0.5 to 1.0 mm. Finally, the AC sample was dried in an oven at 110 °C for 12 hours before use.

2.2 Pyrolysis of WCO

The pyrolysis tests conducted in this study were laboratory-scale batch operations. The reactor used was a 1-liter, two-necked quartz round-bottom flask equipped with a mass flow controller and a nitrogen gas cylinder (Fig. 1). A mixture of 100 g of WCO feedstock and a carbonaceous catalyst with varying BET surface areas was prepared using AC:WCO mass ratios of 1:40, 1:30, and 1:20. Each batch was then loaded into the reactor. To ensure an oxygen-free environment and prevent leakage, the system was purged with nitrogen gas at a constant flow rate of 40 ml/min for 10 minutes before heating. A thermocouple probe was inserted into the reactor, making direct contact with the WCO sample. The reaction temperature was continuously monitored throughout the pyrolysis tests. The samples were stirred at a speed of 40 rpm throughout the experiment and heated using an electric magnetic stirrer heating mantle. The temperature was raised at a rate of 20 °C/min until the targeted pyrolysis temperatures of 375, 400, and 425 °C were reached. The temperature was then maintained for 30 minutes.

During the experiments, the pyrolysis vapors were directed to a condenser unit maintained at 10 °C. The vapors were condensed into liquid bio-oil, which was collected in a flask, while the excess vapors were collected in a gas sampling bag for further analysis. The weight of the liquid bio-oil was determined, and its yield was calculated using Equation (1). The remaining unpyrolyzed residues at the bottom of the reactor were collected and weighed. The energy conversion of the liquid bio-oil produced from the catalytic WCO pyrolysis was calculated using Equation (2).[19,33]

$$\text{Liquid yield, wt\%} = \frac{\text{Liquid yield output (g)}}{\text{WCO feed (g)}} \times 100 \qquad (1)$$

$$\text{Energy conversion, \%} = \frac{(\text{Weight of bio}-\text{oil})(\text{bio}-\text{oil}'\text{s heating value})}{(\text{Weight of WCO})(\text{WCO}'\text{s heating value})} \times 100 \qquad (2)$$

2.3 Experimental design and optimum condition based on RSM

The RSM method was employed to explore the optimal operating parameters for achieving the highest energy conversion values based on the heating values of liquid bio-oils. The independent factors considered were reaction temperature, the AC to WCO ratio, and BET surface area while the dependent parameters were the yield of liquid bio-oil and its heating values. The RSM technique used a CCD to determine the number of experiments. The significance of each factor was assessed through batch experiments. The CCD operation involved identifying the precise ranges and levels of the three independent parameters, as indicated in Table 1.

RSM was then used to examine the highest level of energy conversion derived from the production of liquid bio-oil while also determining the most favorable operating parameters. The influence of each individual factor and their interactions on the response variable was assessed using regression ANOVA. Equation (3) represents a second-order polynomial equation used to model the data.

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} {X_i}^2 + \sum_{i=1}^{k} \sum_{j=i+1}^{k} b_{ij} X_i X_j + \varepsilon \qquad (3)$$

where Y represents the predicted response used as a dependent variable; k is the number of variables studied in the experiments; b_0 is the intercept; b_i is the linear coefficient; b_{ii} is the quadratic coefficient; b_{ij} is the interaction coefficient; X_i and X_j are the independent variables, and ε is the error of the model.

Table 1. Experimental range and levels of independent variables.

Independent Parameters	Unit	Symbol	Range and Level		
			-1	0	1
Temperature	˚C	X_1	375	400	425
AC: WCO ratio	g/g	X_2	1:40	1:30	1:20
BET surface area	m^2/g	X_3	500	750	1000

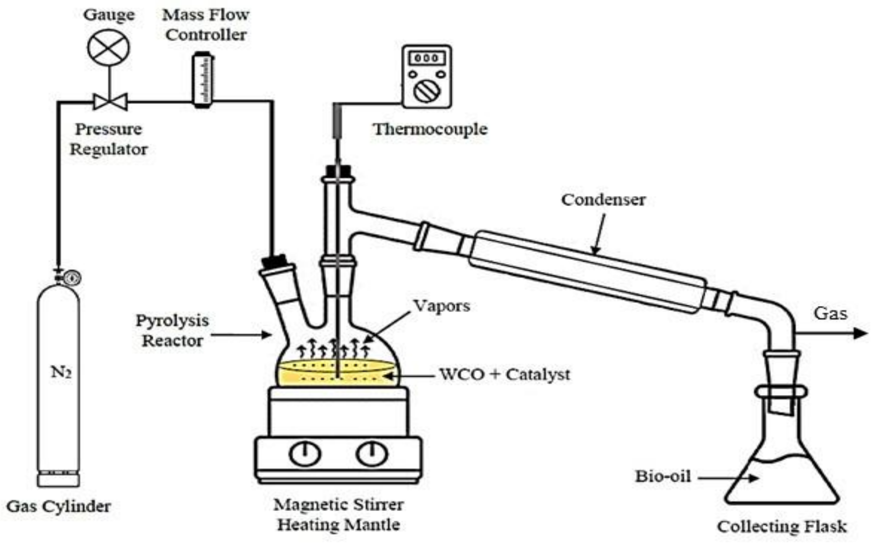


Fig. 1 Schematic diagram of the pyrolysis of WCO experiment.

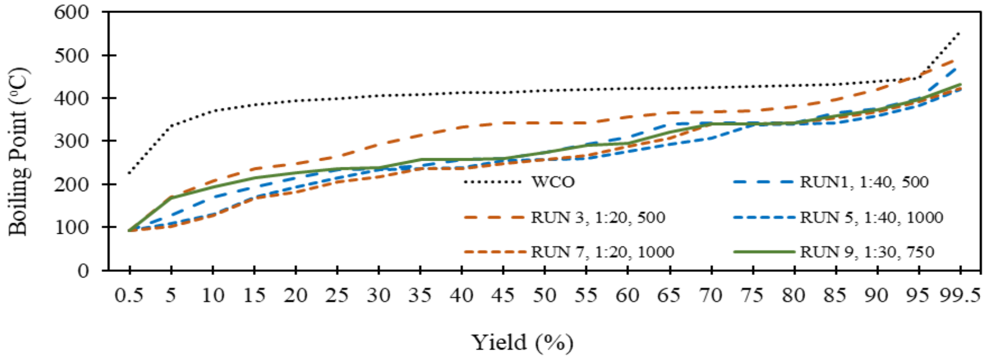
2.4 WCO and bio-oil characterization techniques

The previous study provided a detailed explanation of the characterization methods used for WCO and bio-oil products.[33] The chemical composition of the bio-oil was determined using a 7890B/5977A gas chromatography-mass spectrometry (GC-MS) system with a mass-selective detector (Agilent, Santa Clara, CA, USA). Fourier-transform infrared (FT-IR) analysis (Thermo Scientific, Waltham, MA, USA) was then performed to identify the functional groups present in the liquid bio-oil. FT-IR spectra were recorded within the wavelength range of 400 to 4000 cm^{-1}. To examine the boiling temperatures corresponding to different carbon chain lengths in the bio-oil, a gas chromatograph equipped with simulated distillation (GC-SIMDIS, Hewlett-Packard HP6890, Agilent, Santa Clara, CA, USA) was used. The boiling points of hydrocarbons with different carbon numbers were classified as follows: C4-C10 (gasoline) below 180 °C, C11-C14 (kerosene) 80 to 250 °C, C15-C20 (diesel) between 250 to 350 °C, and hydrocarbons with carbon numbers above C20 (fuel oil) above 350 °C.[34] The fuel characteristics, including density at 15 °C, kinematic viscosity at 40 °C, calorific value, acid value, and water content of the liquid bio-oil samples, were analyzed using the American Society for Testing and Materials (ASTM) technique as described in the earlier work.[33]

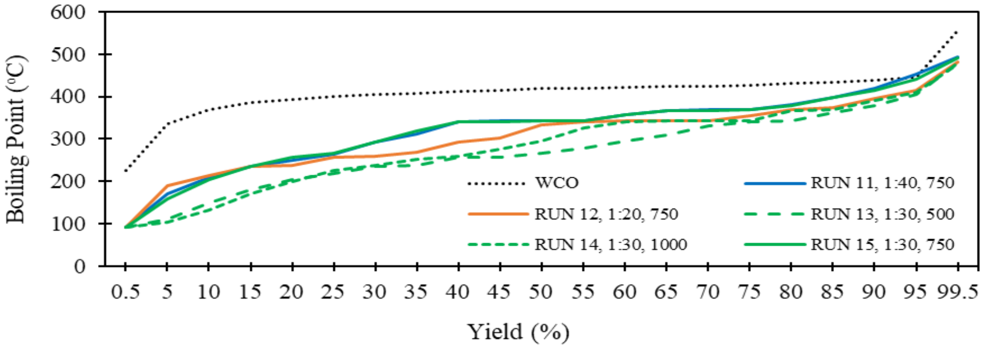
3. Results and discussion

3.1 Simulated distillation temperature profile of the compound distribution of produced liquid bio-oil and WCO

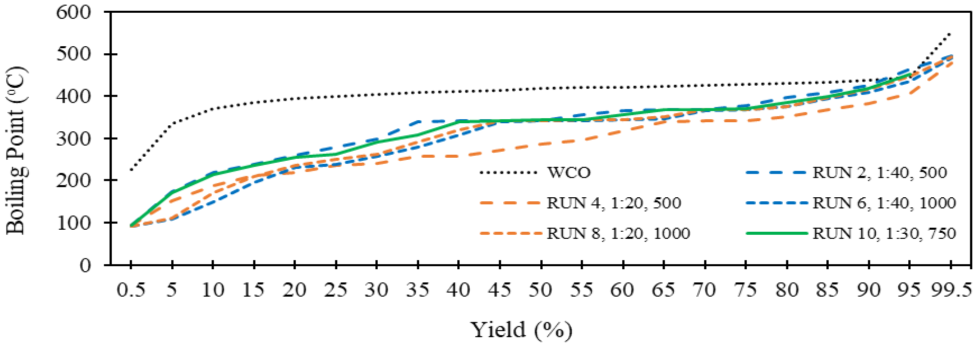
Figure 2 illustrates the distribution of liquid bio-oil compounds (% yield) as a function of the simulated distillation temperature (boiling point) at various reaction temperatures. Based on the GC-SIMDIS analysis, it was observed that more than 90 wt% of the compounds in WCO were distilled at temperatures above 350 °C, indicating the presence of heavy



(a) At 375 °C



(b) At 400 °C



(c) At 425 °C

Fig. 2 Simulated distillation temperature profile of produced liquid bio-oil from catalytic WCO pyrolysis at various temperatures: (a) 375 °C, (b) 400 °C and (c) 425 °C.

compounds with carbon chain lengths greater than 20. These compounds include palmitic acid, oleic acid, and linoleic acid.[35] When examining the compound distribution in liquid bio-oil derived from WCO pyrolysis, it was found that the distillation temperatures shifted downward, particularly in the range of 100 to 350 °C. This significant shift in the boiling points across all runs suggests an increased presence of lighter, lower-carbon-chain compounds in the liquid bio-oil. Catalytic WCO pyrolysis facilitated the breakdown of complex, high-carbon-chain molecules into more valuable, lighter products.

Additionally, it was observed that the AC:WCO ratio and BET surface area had a minor effect on the compound distribution at higher reaction temperatures (400 °C and 425 °C), as shown in Figs. 2b and 2c, respectively. However, at the lower temperature of 375 °C (Fig. 2a), the BET surface area had a more significant effect. Specifically, at a constant AC:WCO ratio, increasing the BET surface area of AC led to a decrease in the distillation temperatures of the liquid bio-oil, indicating a greater concentration of lower-carbon-chain compounds. Conversely, when the BET surface area was held constant, an increase in the AC dosage resulted in higher distillation temperatures, signifying the presence of larger, high-carbon-chain molecules. Therefore, to optimize the production of economically valuable alternative energy, it is crucial to prioritize conditions that not only enhance yield and energy conversion but also improve the economic feasibility of the process. This includes balancing the process parameters to favor the production of lower-carbon-chain compounds that are more suitable for use as fuel.

3.2 Polynomial equation for catalytic WCO pyrolysis

Table 2 presents the yields and heating values of bio-oil obtained from the WCO pyrolysis experiments. The bio-oil yields from 16 experiments varied from 53.75% to 87.82%, while the measured heating values ranged from 38.11 to 41.35 kJ/g. It was observed that the process conditions leading to the highest bio-oil yield did not correspond to the highest heating value, and vice versa. Therefore, as shown in Table 2, energy conversion depends on both the yield and the heating value of the bio-oil produced. In addition, the predicted energy conversion was calculated using the polynomial equation derived from Equation (3), with coefficients obtained from the regression model, as shown in Equation (4).

$$Y = -1925.8731 + 9.5950X_1 - 1766.0099X_2 + 0.0364X_3 - 0.0113X_1^2 + 58409.7350X_2^2 - 0.0001X_3^2 - 6.0062X_1X_2 + 0.0003X_1X_3 - 0.3113X_2X_3 \quad (4)$$

where Y represents energy conversion, X_1 represents reaction temperature, X_2 represents the AC:WCO ratio, X_3 represents the BET surface area of AC, X_1X_2, X_1X_3, and X_2X_3 represent interaction coefficients, and X_1^2, X_2^2, and X_3^2 represent squared coefficients.

The optimal experimental condition, as indicated in Table 2, was achieved during the sixth run with an AC:WCO ratio of 1:40, a reaction temperature of 425 °C, and a BET surface area of 1000 m^2/g. Under these conditions, the experiment yielded a maximum energy conversion of 88.14%, while the model predicted a value of 89.36%. Further analysis revealed a maximum energy conversion of 93.41%, achieved under the following conditions: a reaction temperature of 425 °C, an AC:WCO ratio of 1:40, and a BET surface area of 757.58 m^2/g. The experimental design using RSM successfully reached the optimal conditions for producing liquid bio-oil with the maximum energy conversion.

To assess the significance of each process parameter, the P-values obtained from ANOVA were analyzed. According to

Table 2. Experimental design and results of the energy conversion of liquid bio-oil yields from WCO pyrolysis.

Run	Parameter			Bio-oil yield (wt%)	Heating value (kJ/g)	Energy conversion (%)	
	X_1 (°C)	X_2 (AC:WCO)	X_2 (m^2/g)			Experimental	Predicted
1	375	1:40	500	62.11	40.03	63.64	60.67
2	425	1:40	500	85.33	40.09	87.56	87.71
3	375	1:20	500	66.58	38.76	66.05	65.84
4	425	1:20	500	85.31	40.27	87.92	85.37
5	375	1:40	1000	53.75	38.20	52.54	55.85
6	425	1:40	1000	87.82	39.21	88.14	89.36
7	375	1:20	1000	59.60	38.09	58.10	57.13
8	425	1:20	1000	83.02	38.24	81.24	83.13
9	375	1:30	750	57.43	38.11	56.02	56.86
10	425	1:30	750	85.18	39.14	85.34	84.63
11	400	1:40	750	85.35	40.20	87.81	86.10
12	400	1:20	750	79.09	41.35	83.71	85.57
13	400	1:30	500	69.34	38.33	68.03	73.61
14	400	1:30	1000	77.93	38.18	76.16	70.77
15	400	1:30	750	78.83	38.61	77.91	77.81
16	400	1:30	750	78.67	38.74	77.99	77.81

Table 3, a P-value below 0.05 indicates that the parameter is statistically significant.[22-24] The research shows that the linear term, reaction temperature (X_1), had a notable impact on the model. Additionally, the squared terms X_1^2 and X_2^2 are also significant variables, as their P-values are below 0.05. Although some parameters may not show statistical significance, they are still included in the equation to ensure accurate predictions, as each component contributes to generating precise outcomes.[27]

Furthermore, an ANOVA was performed to confirm the statistical significance of the regression model. The ANOVA results for the RSM are shown in Table 4. The coefficient of determination (R^2) value of 0.9565 and the adjusted R^2 value of 0.8911 indicate a high degree of precision and dependability in the 16 experimental runs represented in Fig. 3. The model's F-value was determined to be 0.0020, which is below the significance threshold of 0.05. Therefore, the polynomial equation model is considered statistically significant at the 95% confidence level.[22,23,26-28] Additionally, it can be concluded that the polynomial equation effectively predicts the liquid bio-oil yield in terms of energy conversion, considering the heating value of the three variable parameters: reaction temperature, AC:WCO ratio, and the BET surface area of AC.

3.3 Effect of process parameters on energy conversion

Figure 4 presents both 3-D and 2-D response surface plots illustrating the effects of temperature and the AC:WCO ratio, temperature and BET surface area, and BET surface area and the AC:WCO ratio on the energy conversion of liquid bio-oil in the WCO pyrolysis process. These factors are identified as the primary influencers. The response surface plots shown in Figs 4a and 4b demonstrate the interaction between temperature and the AC:WCO ratio (X_1X_2) and between

Table 3. Coefficients for the polynomial equation in the response surface model of catalytic pyrolysis of WCO.

Source	Coefficients	Standard Error	t Stat	P-value	Remark
Intercept	-1925.8731	637.8940	-3.0160	0.0235	
X_1	9.5950	3.2370	2.9620	0.0252	
X_2	-1769.0099	2332.8900	-0.7590	0.4768	Significant
X_3	0.0365	0.1120	0.3240	0.7571	Significant
X_1^2	-0.0113	0.0040	-2.7960	0.0313	
X_2^2	58409.7350	18416.7760	3.1740	0.0192	
X_3^2	-0.0001	0.0000	-2.2350	0.0669	Significant
$X_1 X_2$	-6.0062	4.5810	-1.3110	0.2377	Significant
$X_1 X_3$	0.0003	0.0002	1.1180	0.3064	
$X_2 X_3$	-0.3113	0.4580	-0.6790	0.5222	

Table 4. ANOVA for response surface model of catalytic pyrolysis of WCO.

Source	Degree of freedom	Sum of square	Mean square	F-value	Significance F
Regression	9	2208.1820	245.3540	14.6401	0.0020
Residual error	6	100.5490	16.7580		
Total	15	2308.7320			

$R^2 = 0.9565$, adjusted $R^2 = 0.8911$

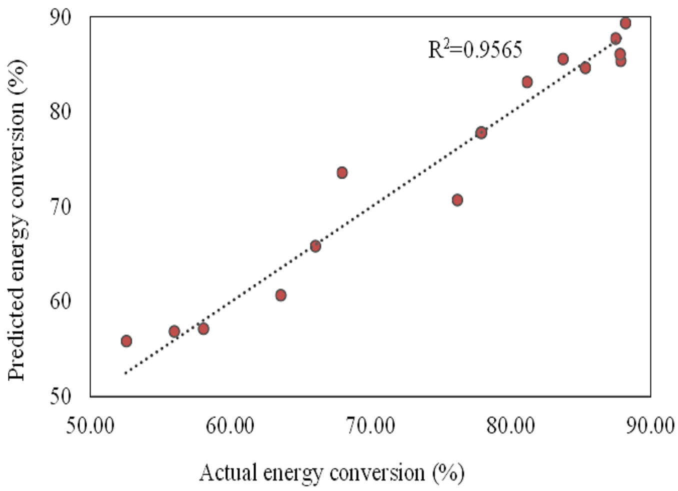


Fig. 3 Statistical analysis of the actual and predicted energy conversions from the production of bio-oils under the studied conditions.

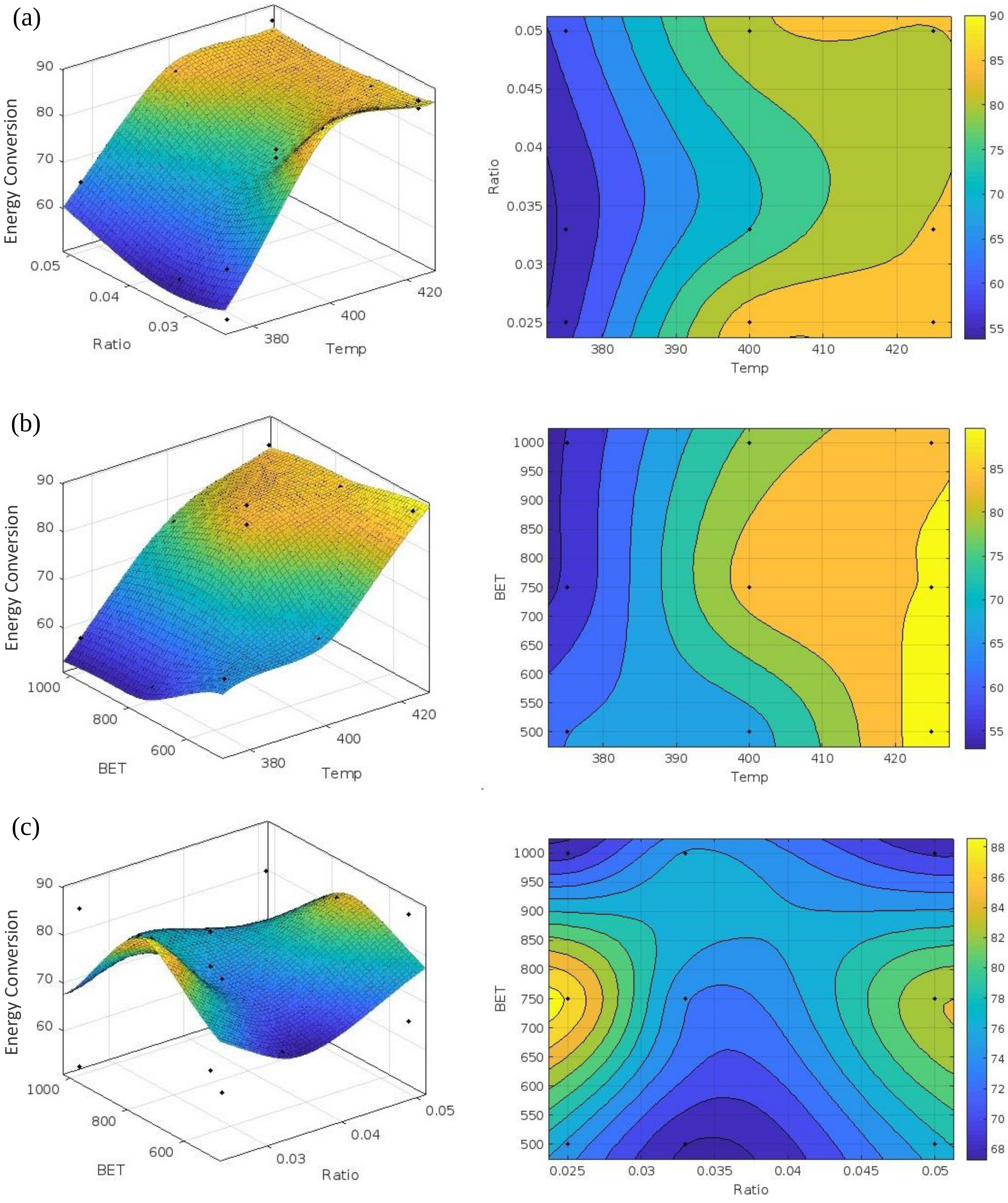


Fig. 4 3-D and 2-D surface response plots showing the effect of (a) temperature and AC:WCO ratio (hold BET value at 750), (b) temperature and BET (hold AC:WCO value at 1:30), and (c) BET and AC:WCO ratio (hold temperature value at 400 °C) on liquid bio-yield produced from WCO pyrolysis.

temperature and BET surface area (X_1X_3), respectively. It was observed that the energy conversion of liquid bio-oil yield improved from 56.86% to 84.63% as the reaction temperature increased from 375 to 425 °C, under constant conditions of a BET surface area of 750 m^2/g and an AC:WCO ratio of 1:30. These parameters significantly impacted the energy conversion of liquid bio-oil, with the optimal temperature range being 400 to 425 °C. As the temperature increased, the yield of liquid bio-oil produced also rose. However, beyond the optimal temperature, the yield was due to secondary decomposition, which led to an increase in gas production.[36] Therefore, to achieve an economically efficient catalytic WCO pyrolysis process that maximizes both liquid bio-oil yield and energy conversion, the process can be operated at temperatures as low as 400 °C, with a maximum temperature of 425 °C. This approach helps to conserve energy and minimize power consumption.[26]

A high P-value of 0.4768 indicates that the AC:WCO ratio

(X_2) did not significantly affect the energy conversion in liquid bio-oil from WCO pyrolysis. However, the interaction term X_2^2 showed a P-value of 0.0192, indicating statistical significance. As depicted in Figs. 4a and 4c, the response surface plots reveal that the energy conversion increased to 86.10% when the smallest amount of AC (1:40) was used. Therefore, to minimize the cost of catalyst utilization, it is unnecessary to use a ratio of AC:WCO greater than 1:40.

The BET surface area (X_3), with a P-value of 0.7571, was found to be non-significant in relation to WCO pyrolysis. As shown in Fig. 4c, when the temperature and AC:WCO ratio remained constant, the increase of liquid bio-oil yield with rising BET surface area was minimal and not substantial. The interaction term X_3^2 exhibited a P-value of 0.0669, which exceeds the threshold of 0.05, indicating that this interaction had a less significant effect. However, it still had a positive influence, as indicated in Equation (3). Therefore, a high BET surface area of AC was not necessary for the WCO pyrolysis process. While an elevated BET surface area is important for the adsorption-desorption process, pyrolysis itself is a thermal decomposition process. Consequently, AC acts as a catalyst, facilitating heat transfer and raising the reaction temperature. This helps in breaking down long carbon-chain compounds into lighter ones, which then transform into condensable gases, leading to higher production of liquid bio-oil.[19,20,37]

3.4 Liquid bio-oil characterization

A liquid bio-oil obtained under an AC:WCO ratio of 1:40, a reaction temperature of 425 °C, and a BET surface area of 1000 m^2/g was analyzed for its physical properties and composition. The chemical composition was determined using GC-MS analysis. Fig. 5 shows the weight percentages of the main components found in the liquid bio-oil. The liquid bio-oil obtained from the pyrolysis of WCO contained 31.96 wt% hydrocarbon compounds and 68.04 wt% oxygenated chemicals. The hydrocarbons included 21.38 wt% alkanes, 10.47 wt% alkenes, and a minimal 0.11 wt% alkynes. The oxygenated chemicals consisted of 44.82 wt% carboxylic acids, 12.85 wt% alcohols, 3.86 wt% esters, 3.47 wt% ketones, and 1.62 wt% aldehydes.

Previous studies have identified similar compounds in bio-oils produced from the pyrolysis of various triglyceride feedstocks. For instance, Trabelsi *et al.*[38] found that the main components of bio-oil from WCO pyrolysis were 89.61 wt% carboxylic acids, 2.31 wt% linear saturated hydrocarbons, 3.64 wt% linear unsaturated hydrocarbons, 0.17 wt% cyclic hydrocarbons, 1.86 wt% alcohols, 0.25 wt% ketones, and 0.25 wt% aldehydes. Similarly, Kraiem *et al.*[39] used GC-MS to identify the chemical composition of bio-oil from WCO pyrolysis, which included 53.11 wt% carboxylic acids, 1.71 wt% aldehydes, 1.21 wt% ketones, and 0.93 wt% alcohols. The hydrocarbons comprised 4.03 wt% linear saturated, 28.65 wt% unsaturated, and 9.54 wt% cyclic compounds. These findings highlight the significant presence of hydrocarbon constituents, particularly carboxylic acids, which are closely linked to the elevated levels of fatty acids in WCO.

Ngo *et al.* [21] also analyzed the chemical composition of bio-oil from soybean oil pyrolysis in a fixed-bed reactor, using various catalysts and GC-MS analysis. Their results revealed that the bio-oil primary comprised of organic compounds with carbon chains ranging from C5 to C11 (21.7% of the total) and C12 to C18 (17.8% of the total).

Figure 6 shows the distribution of bio-oil separated at various temperature ranges using GC-SIMDIS. The liquid bio-oil was categorized into different types based on their boiling.[33,34] Under the optimal experimental conditions, the primary constituents of the bio-oil were diesel-like compounds, which accounted for 40.00% of the total. These were followed by fuel oil-like compounds at 34.00%, kerosene-like compounds at 14.00%, and gasoline-like compounds at 12.00%, as shown in Fig. 6a. With the use of AC, the proportion of diesel-like compounds increased from

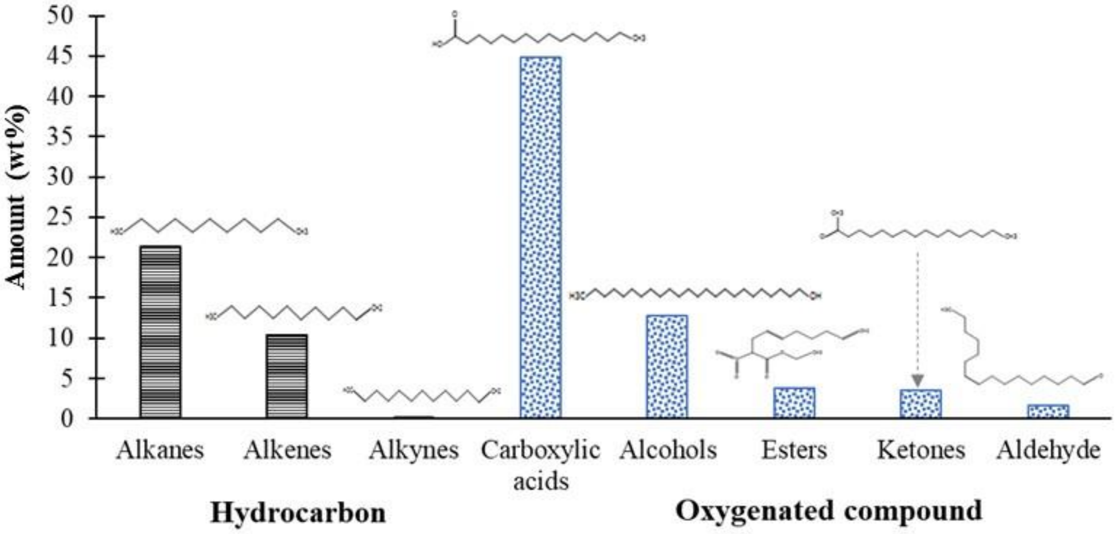
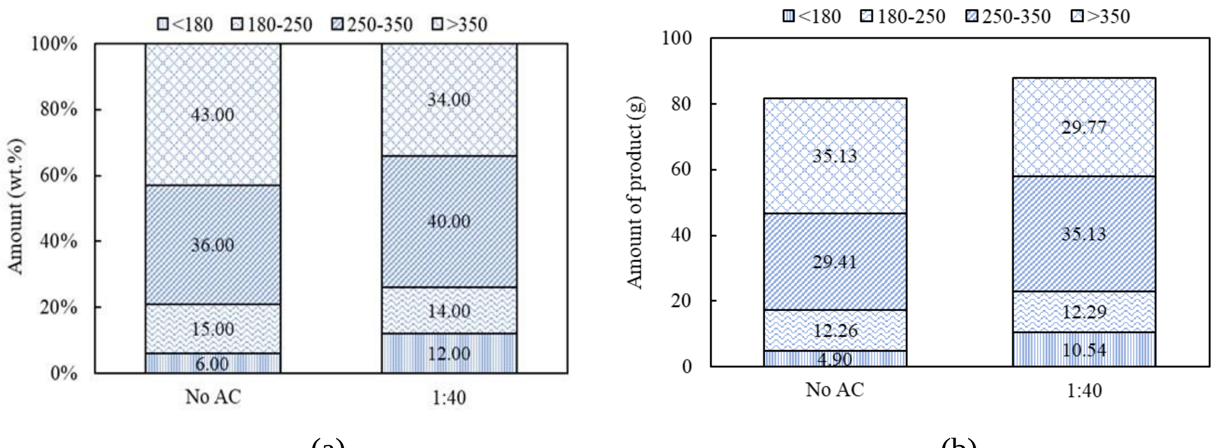


Fig. 5 Major group of organic compositions in liquid bio-oil obtained under a ratio of AC to WCO of 1:40, a reaction temperature of 425 °C, and a BET surface area of 1000 m^2/g.



(a) (b)

Fig. 6 The comparison of fractionated compounds between liquid bio-oil obtained under a ratio of AC to WCO of 1:40, a reaction temperature of 425 °C, and a BET surface area of 1000 m^2/g and bio-oil obtained from a reaction temperature of 425 °C with the absence of AC according to the boiling temperature distribution by GC-SIMDIS analysis. (a) Product distribution by percentage; (b) yield of liquid bio-oil and product distribution by amount.

36.00% to 40.00%, while the proportion of gasoline-like compounds rose from 6.00% to 12.00%.

The liquid bio-oil yield, presented in Fig. 6b, is also an important consideration. When AC was used, the yield of liquid bio-oil increased from 81.70 g to 87.73 g. Of this amount, diesel-like compounds accounted for a maximum of 35.25 g. The primary degradation mechanism for triglycerides in WCO was direct pyrolysis. AC acted as a heat-transfer agent, enhancing the pyrolysis reaction temperature by facilitating the thermal cracking of heavy carbon compounds (43%),[18,19,33] leading to the formation of lighter carbon compounds (34%) and the production of more valuable products, such as diesel-like compounds in the liquid bio-oil.[26]

Figure 7 presents the FT-IR spectrum, which reveals the functional groups of organic compounds in the liquid bio-oil obtained under optimal operating conditions. The wave number range between 2916 and 2848 cm^{-1} displayed distinct peaks attributed to carboxylic acids and alkanes. The significant height of these peaks indicates a high concentration of saturated aliphatic hydrocarbons in the bio-oil. Additional aliphatic groups were indicated by peaks in the range of 1464 to 1430 cm^{-1}, further confirming the aliphatic nature of the bio-oil. The presence of oxygen in the bio-oil was confirmed by a peak at 1702 cm^{-1}, corresponding to the C=O stretching vibration, which suggests the presence of carbonyl groups such as aldehydes, ketones, esters, and carboxylic acids. Furthermore, C-O stretching vibrations were observed in the spectral range of 1292 to 1188 cm^{-1}, indicative of esters, ethers, alcohols, and carboxylic acids. Weaker bands in the range of 938 to 686 cm^{-1}, attributed to C-H bending, signaled the presence of alkenes and aromatics in the bio-oil. The bio-oil obtained in this study was predominantly composed of carboxylic acids, aliphatic hydrocarbons, and small amounts of aromatics, aldehydes, and ketones. These findings align with the organic chemical groups identified in the GC-MS analysis. A similar FT-IR comparison was conducted by

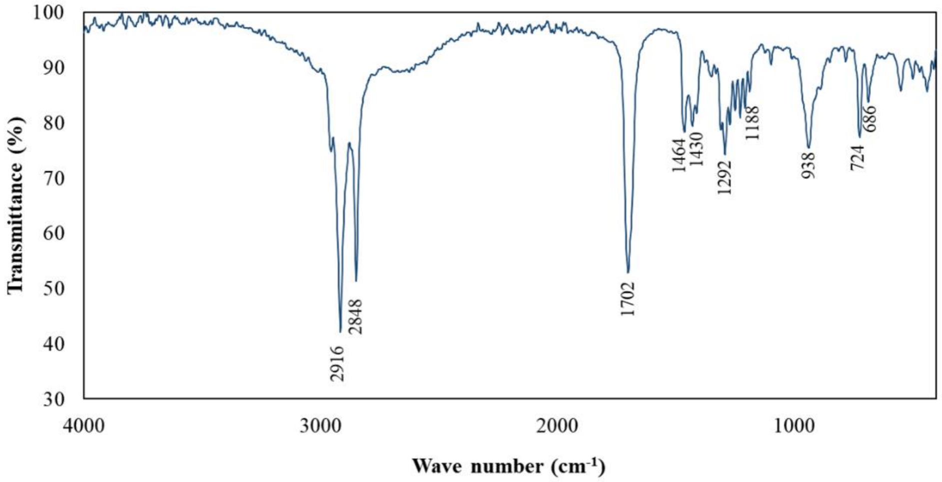


Fig. 7 FT-IR spectra of liquid bio-oil obtained under a ratio of AC to WCO of 1:40, a reaction temperature of 425 °C, and a BET surface area of 1000 m^2/g.

Table 5. Fuel properties of liquid bio-oil compared to ASTM and EN biodiesel standards.

Fuel Properties	WCO	Bio-oil[a]	ASTM Standard[b]	EN Standard[b]	Diesel[c]
Density at 15°C (kg/m^3)	910	890	860-900	860-900	810-870
Viscosity at 40°C (cSt.)	43.0	11.6	1.9-6.0	3.5-5.0	1.8-4.1
Calorific value (kJ/g)	38.3	39.2	-	-	>45.0
Water content (%)	0.7	0.3	<0.5	<0.5	<0.5
Acid value (mgKOH/g)	5.4	126.7	<0.5	<0.5	<0.5

[a] Bio-oil from this work; [b] Biodiesel standard[41]; [c] Specification of diesel[42-46].

Qasim *et al.*, who compared the FT-IR spectrum of liquid bio-oil with those of diesel fuel and biodiesel derived from a blend of transesterified waste canola and waste transformer oils. Their study revealed that the liquid bio-oil shared similarities with diesel and biodiesel fuels, particularly in the presence of aliphatic components with notable intensity.[40] However, a noticeable difference was observed in the magnitude of peaks associated with oxygenated components in the liquid bio-oil. The physical properties of the liquid bio-oil, obtained under a 1:40 AC to WCO ratio, a reaction temperature of 425 °C, and a BET surface area of 1000 m^2/g, including density, kinematic viscosity, water content, calorific value, and acid value, were analyzed and compared with the standards for diesel and biodiesel according to ASTM and European (EN) Standards. The results are presented in Table 5.

The liquid bio-oil had a density of 890 kg/m^3 at 15 °C, which falls within the acceptable range set by ASTM and EN standards. However, it is slightly higher than the density specification for diesel fuel, which ranges from 810 to 870 kg/m^3. These findings are consistent with other studies, which report that the density of pyrolytic bio-oil from WCO pyrolysis typically ranges from 880 to 899 kg/m^3.[33,38,43] This suggests that liquid bio-oil could be used as engine fuel without requiring further adjustments to density. The kinematic viscosity at 40 °C was 11.6 cSt, which exceeds both the ASTM and EN biodiesel standards, as well as the viscosity range for diesel fuel. However, it is within the range reported in previous studies on pyrolytic bio-oils obtained from triglyceride pyrolysis.[46]

The liquid bio-oil exhibited a calorific value of 39.2 kJ/g, which is lower than the specification for diesel fuel. This aligns with previous research, where pyrolytic bio-oil from the WCO pyrolysis had a lower heating value of 36.9 kJ/g.[47] Despite this, the findings suggest that the liquid bio-oil holds considerable promise as a feedstock for synthetic gasoline production. The water content of the liquid bio-oil was 0.3%, which is within the acceptable range for both biodiesel and diesel fuel (<0.5%). However, a key drawback was its acid value, which measured 126.7 mg KOH/g. The pyrolysis process typically converts triglycerides in WCO into acids through thermal cracking.[17,33] This value exceeds the criteria set by ASTM and EN standards. Nevertheless, it is consistent with acid values reported in previous studies, which range from 124.3 to 126.8 mg KOH/g.[16,17,32,33,40,47] The high acidity indicates a significant presence of oxygenated compounds, particularly carboxylic acids, as confirmed by the GC-MS and FT-IR analysis results (Figs. 5 and 7).

To make the bio-oil suitable for engine fuel, it is essential to reduce the acidic components through (hydro)deoxygenation and catalytic esterification, as these can cause corrosion and clogging in engine systems.[48,49] Despite the high acidity, this work demonstrates that the pyrolysis of WCO can produce a valuable liquid fuel that holds the potential for further enhancement to meet commercial diesel fuel standards, surpassing the specifications for biodiesel and diesel fuel.

4. Conclusions

RSM proves to be an efficient approach for predicting energy conversion in the production of liquid bio-oil from WCO pyrolysis. One of its key advantages is its ability to provide accurate predictions with a minimal number of experimental trials. The optimal operational parameters, which resulted in a maximum energy conversion of 93.41% and liquid bio-oil production of 87.82%, were a reaction temperature of 425 °C, an AC:WCO ratio of 1:40, and a BET surface area of 757.58 m^2/g. Regression analysis revealed a strong correlation between the quadratic model equation and the experimental data, with a coefficient of determination (R^2) of 0.9567 and an F-value of 14.6401. These findings indicated that temperature had the greatest influence on both liquid bio-oil production and energy conversion throughout the process. The fuel characteristics of liquid bio-oil obtained from the optimal experimental conditions, including density and water content, met the biodiesel requirements set by ASTM and EN standards and demonstrated a high calorific value. However, further refinement of the targeted products can be achieved by investigating various catalysts and extending applications to other processes, such as (hydro)deoxygenation and catalytic esterification, to reduce oxygenated compounds that contribute to the acidity in bio-oil. Additionally, distillation could be considered as a potential method to further enhance the product quality.

Acknowledgements

This work was supported by the Thailand Science Research and Innovation Fundamental Fund, fiscal year 2023 (TUFF42/2566). WB thanks to the Faculty of Engineering, Thammasat University, for providing the Graduate Thesis Grant.

Conflict of Interest

There is no conflict of interest.

Supporting Information

All experimental data in this article will be made available upon request by the authors.

References

[1] Q. Zhang, T. Wang, Y. Xu, Q. Zhang, L. Ma, Production of liquid alkanes by controlling reactivity of sorbitol hydrogenation with a Ni/HZSM-5 catalyst in water, *Energy Conversion and Management*, 2014, **77**, 262-268, doi: 10.1016/j.enconman.2013.09.032.

[2] Q. Lu, W.-Z. Li, X.-F. Zhu, Overview of fuel properties of biomass fast pyrolysis oils, *Energy Conversion and Management*, 2009, **50**, 1376-1383, doi: 10.1016/j.enconman.2009.01.001.

[3] M. V. Singh, S. Kumar, M. Sarker, Waste HD-PE plastic, deformation into liquid hydrocarbon fuel using pyrolysis-catalytic cracking with a $CuCO_3$ catalyst, *Sustainable Energy & Fuels*, 2018, **2**, 1057-1068, doi: 10.1039/c8se00040a.

[4] M. V. Singh, Deformation of virgin HD-PE, PP and waste PP Plastics into green fuel via a Pyrolysis-catalytic using a $NiCO_3$ catalyst, *Indian Chemical Engineer*, 2019, **61**, 254-268, doi: 10.1080/00194506.2018.1548949.

[5], M. V. Singh, Pyrolysis of waste polyolefins into liquid petrochemicals using metal carbonate catalyst, *Engineered Science*, 2022, **19**, 285-291, doi: 10.30919/es8d699.

[6] M. V. Singh, Pyrolysis processes and physiochemical properties of liquid hydrocarbon fuel from waste plastics, *Chemical Engineering & Technology*, 2023, **46**, 1411-1423, doi: 10.1002/ceat.202200519.

[7] M. V. Singh, Conversions of waste tube-tyres (WTT) and waste polypropylene (WPP) into diesel fuel through catalytic pyrolysis using base $SrCO_3$, *Engineered Science*, 2021, **13**, 87-97, doi: 10.30919/es8d1158.

[8] S. S. Kim, S. H. Kim, Pyrolysis kinetics of waste automobile lubricating oil, *Fuel*, 2000, **79**, 1943-1949, doi: 10.1016/s0016-2361(00)00028-4.

[9] Y. Wang, L. Dai, L. Fan, D. Duan, Y. Liu, R. Ruan, Z. Yu, Y. Liu, L. Jiang, Microwave-assisted catalytic fast co-pyrolysis of bamboo sawdust and waste tire for bio-oil production, *Journal of Analytical and Applied Pyrolysis*, 2017, **123**, 224-228, doi: 10.1016/j.jaap.2016.11.025.

[10] Y. Zhou, Y. Wang, L. Fan, L. Dai, D. Duan, Y. Liu, R. Ruan, Y. Zhao, Z. Yu, Y. Hu, Fast microwave-assisted catalytic co-pyrolysis of straw stalk and soapstock for bio-oil production, *Journal of Analytical and Applied Pyrolysis*, 2017, **124**, 35-41, doi: 10.1016/j.jaap.2017.02.026.

[11] A. Orjuela, J. Clark, Green chemicals from used cooking oils: trends, challenges, and opportunities, *Current Opinion in Green and Sustainable Chemistry*, 2020, **26**, 100369, doi: 10.1016/j.cogsc.2020.100369.

[12] I. Thushari, S. Babel, Comparative study of the environmental impacts of used cooking oil valorization options in Thailand, *Journal of Environmental Management*, 2022, **310**, 114810, doi: 10.1016/j.jenvman.2022.114810.

[13] P. Intarapong, S. Papong, P. Malakul, Comparative life cycle assessment of diesel production from crude palm oil and waste cooking oil via pyrolysis, *International Journal of Energy Research*, 2016, **40**, 702-713, doi: 10.1002/er.3433.

[14] J. Xu, J. Jiang, J. Zhao, Thermochemical conversion of triglycerides for production of drop-in liquid fuels, *Renewable and Sustainable Energy Reviews*, 2016, **58**, 331-340, doi: 10.1016/j.rser.2015.12.315.

[15] M. S. Graboski, R. L. McCormick, Combustion of fat and vegetable oil derived fuels in diesel engines, *Progress in Energy and Combustion Science*, 1998, **24**, 125-164, doi: 10.1016/s0360-1285(97)00034-8.

[16] A. Demirbas, Relationships derived from physical properties of vegetable oil and biodiesel fuels, *Fuel*, 2008, **87**, 1743-1748, doi: 10.1016/j.fuel.2007.08.007.

[17] D. Chiaramonti, M. Buffi, A. M. Rizzo, G. Lotti, M. Prussi, Bio-hydrocarbons through catalytic pyrolysis of used cooking oils and fatty acids for sustainable jet and road fuel production, *Biomass and Bioenergy*, 2016, **95**, 424-435, doi: 10.1016/j.biombioe.2016.05.035.

[18] S. S. Lam, R. K. Liew, A. Jusoh, C. T. Chong, F. N. Ani, H. A. Chase, Progress in waste oil to sustainable energy, with emphasis on pyrolysis techniques, *Renewable and Sustainable Energy Reviews*, 2016, **53**, 741-753, doi: 10.1016/j.rser.2015.09.005.

[19] S. S. Lam, W. A. Wan Mahari, A. Jusoh, C. T. Chong, C. L. Lee, H. A. Chase, Pyrolysis using microwave absorbents as reaction bed: an improved approach to transform used frying oil into biofuel product with desirable properties, *Journal of Cleaner Production*, 2017, **147**, 263-272, doi: 10.1016/j.jclepro.2017.01.085.

[20] L. Li, Z. Ding, K. Li, J. Xu, F. Liu, S. Liu, S. Yu, C. Xie, X. Ge, Liquid hydrocarbon fuels from catalytic cracking of waste cooking oils using ultrastable zeolite USY as catalyst, *Journal of Analytical and Applied Pyrolysis*, 2016, **117**, 268-272, doi: 10.1016/j.jaap.2015.11.006.

[21] T.-A. Ngo, J. Kim, S. K. Kim, S.-S. Kim, Pyrolysis of soybean oil with H-ZSM5 (Proton-exchange of Zeolite Socony Mobil#5) and MCM41 (Mobil Composition of Matter No. 41) catalysts in a fixed-bed reactor, *Energy*, 2010, **35**, 2723-2728, doi: 10.1016/j.energy.2009.05.023.

[22] F. Abnisa, W. M. A. Wan Daud, J. N. Sahu, Optimization and characterization studies on bio-oil production from palm shell by pyrolysis using response surface methodology, *Biomass and Bioenergy*, 2011, **35**, 3604-3616, doi: 10.1016/j.biombioe.2011.05.011.

[23] F. Abnisa, W. M. A. Wan Daud, A review on co-pyrolysis of biomass: an optional technique to obtain a high-grade pyrolysis oil, *Energy Conversion and Management*, 2014, **87**, 71-85, doi: 10.1016/j.enconman.2014.07.007.

[24] J. Mabrouki, M. A. Abbassi, K. Guedri, A. Omri, M. Jeguirim, Simulation of biofuel production via fast pyrolysis of palm oil residues, *Fuel*, 2015, **159**, 819-827, doi:

10.1016/j.fuel.2015.07.043.

[25] X. Zhuang, Z. Gan, K. Cen, Y. Ba, F. Chen, D. Chen, Upgrading biochar by co-pyrolysis of heavy bio-oil and apricot shell using response surface methodology, *Fuel*, 2022, **310**, 122447, doi: 10.1016/j.fuel.2021.122447.

[26] M. G. Nayak, A. P. Vyas, Optimization of microwave-assisted biodiesel production from Papaya oil using response surface methodology, *Renewable Energy*, 2019, **138**, 18-28, doi: 10.1016/j.renene.2019.01.054.

[27] M. G. Nayak, A. P. Vyas, Parametric study and optimization of microwave assisted biodiesel synthesis from Argemone Mexicana oil using response surface methodology, *Chemical Engineering and Processing - Process Intensification*, 2022, **170**, 108665, doi: 10.1016/j.cep.2021.108665.

[28] H. M. Kadlimatti, B. Raj Mohan, M. B. Saidutta, Bio-oil from microwave assisted pyrolysis of food waste-optimization using response surface methodology, *Biomass and Bioenergy*, 2019, **123**, 25-33, doi: 10.1016/j.biombioe.2019.01.014.

[29] F. Pinto, J. M. Hidalgo-Herrador, F. Paradela, P. Costa, R. André, J. Fratczak, C. Snape, L. Anděl, J. Kusy, Coal and waste direct liquefaction, using glycerol, polyethylene waste and waste tyres pyrolysis oil. Optimisation of liquids yield by response surface methodology, *Journal of Cleaner Production*, 2020, **255**, 120192, doi: 10.1016/j.jclepro.2020.120192.

[30] S. Neha, N. Remya, Optimization of bio-oil production from microwave co-pyrolysis of food waste and low-density polyethylene with response surface methodology, *Journal of Environmental Management*, 2021, **297**, 113345, doi: 10.1016/j.jenvman.2021.113345.

[31] G. K. Gupta, M. K. Mondal, Bio-energy generation from sagwan sawdust via pyrolysis: product distributions, characterizations and optimization using response surface methodology, *Energy*, 2019, **170**, 423-437, doi: 10.1016/j.energy.2018.12.166.

[32] S. Gupta, P. Patel, P. Mondal, Biofuels production from pine needles via pyrolysis: process parameters modeling and optimization through combined RSM and ANN based approach, *Fuel*, 2022, **310**, 122230, doi: 10.1016/j.fuel.2021.122230.

[33] W. Banchapattanasakda, C. Asavatesanupap, M. Santikunaporn, Conversion of waste cooking oil into bio-fuel via pyrolysis using activated carbon as a catalyst, *Molecules*, 2023, **28**, 3590, doi: 10.3390/molecules28083590.

[34] K-H. Lee, Thermal and catalytic degradation of pyrolytic oil from pyrolysis of municipal plastic wastes, *Journal of Analytical and Applied Pyrolysis*, 2009, **85**, 372-379, doi: 10.1016/j.jaap.2008.11.032.

[35] M. Aslam, N. C. Kothiyal, A. K. Sarma, True boiling point distillation and product quality assessment of biocrude obtained from Mesua ferrea L. seed oil via hydroprocessing, *Clean Technologies and Environmental Policy*, 2015, **17**, 175-185, doi: 10.1007/s10098-014-0774-z.

[36] Q. Xie, M. Addy, S. Liu, B. Zhang, Y. Cheng, Y. Wan, Y. Li, Y. Liu, X. Lin, P. Chen, R. Ruan, Fast microwave-assisted catalytic co-pyrolysis of microalgae and scum for bio-oil production, *Fuel*, 2015, **160**, 577-582, doi: 10.1016/j.fuel.2015.08.020.

[37] S. S. Lam, A. D. Russell, C. L. Lee, H. A. Chase, Microwave-heated pyrolysis of waste automotive engine oil: influence of operation parameters on the yield, composition, and fuel properties of pyrolysis oil, *Fuel*, 2012, **92**, 327-339, doi: 10.1016/j.fuel.2011.07.027.

[38] A. Ben Hassen-Trabelsi, T. Kraiem, S. Naoui, H. Belayouni, Pyrolysis of waste animal fats in a fixed-bed reactor: production and characterization of bio-oil and bio-char, *Waste Management*, 2014, **34**, 210-218, doi: 10.1016/j.wasman.2013.09.019.

[39] T. Kraiem, A. Ben Hassen, H. Belayouni, M. Jeguirim, Production and characterization of bio-oil from the pyrolysis of waste frying oil, *Environmental Science and Pollution Research*, 2017, **24**, 9951-9961, doi: 10.1007/s11356-016-7704-z.

[40] M. Qasim, T. M. Ansari, M. Hussain, Combustion, performance, and emission evaluation of a diesel engine with biodiesel like fuel blends derived from a mixture of Pakistani waste canola and waste transformer oils, *Energies*, 2017, **10**, 1023, doi: 10.3390/en10071023.

[41] I. Barabas, I.-A. Todoru, Biodiesel quality, standards and properties, 2011.

[42] W. A. Wan Mahari, N. F. Zainuddin, C. T. Chong, C. L. Lee, W. H. Lam, S. C. Poh, S. S. Lam, Conversion of waste shipping oil into diesel-like oil via microwave-assisted pyrolysis, *Journal of Environmental Chemical Engineering*, 2017, **5**, 5836-5842, doi: 10.1016/j.jece.2017.11.005.

[43] W. A. Wan Mahari, C. T. Chong, C. K. Cheng, C. L. Lee, K. Hendrata, P. N. Yuh Yek, N. L. Ma, S. S. Lam, Production of value-added liquid fuel via microwave co-pyrolysis of used frying oil and plastic waste, *Energy*, 2018, **162**, 309-317, doi: 10.1016/j.energy.2018.08.002.

[44] D. Hansdah, S. Murugan, L. M. Das, Experimental studies on a DI diesel engine fueled with bioethanol-diesel emulsions, *Alexandria Engineering Journal*, 2013, **52**, 267-276, doi: 10.1016/j.aej.2013.06.001.

[45] R. Mamat, M. R. Hainin, N. Abdul Hassan, N. A. Abdul Rahman, M. N. M. Warid, M. K. Idham, A review of performance asphalt mixtures using bio-binder as alternative binder, *Jurnal Teknologi*, 2015, **77**, 17-20, doi: 10.11113/jt.v77.6681.

[46] I. Kalargaris, G. Tian, S. Gu, The utilisation of oils produced from plastic waste at different pyrolysis temperatures in a DI diesel engine, *Energy*, 2017, **131**, 179-185, doi: 10.1016/j.energy.2017.05.024.

[47] A. Ben Hassen Trabelsi, K. Zaafouri, W. Baghdadi, S. Naoui, A. Ouerghi, Second generation biofuels production from waste cooking oil via pyrolysis process, *Renewable Energy*, 2018, **126**, 888-896, doi: 10.1016/j.renene.2018.04.002.

[48] L. Li, B. Yan, H. Li, S. Yu, X. Ge, Decreasing the acid value of pyrolysis oil via esterification using ZrO_2/SBA-15 as a solid acid catalyst, *Renewable Energy*, 2020, **146**, 643-650, doi: 10.1016/j.renene.2019.07.015.

[49] M. Santikunaporn, T. Techopittayakul, S. Echaroj, S. Chavadej, Y.-H. Chen, M.-H. Yuan, C. Asavatesanupap, Optimization of biodiesel production from waste cooking oil in a continuous mesoscale oscillatory baffled reactor, *Engineering*

Journal, 2020, **24**, 19-28, doi: 10.4186/ej.2020.24.2.19.