Advance Sustainable Science, Engineering and Technology (ASSET)
Vol. 8, No.4, October 2026, pp. 02604039-01 ~ 02604039-013
ISSN: 2715-4211 DOI: https://doi.org/10.26877/asset.v8i4.3705

RSM Optimization of Used Engine Oil Recovery Using Coal-Based Activated Carbon in a Pyrolysis–Distillation Unit

Alwathan[1*], Muh. Irwan[1], Ramli Thahir[1], Sirajuddin[1], Siti Hamidah[2]

[1]Department of Chemical Engineering, Politeknik Negeri Samarinda, Jl. Cipto Mangunkusomu, Samarinda 75131, East Kalimantan, Indonesia

[2]Malaysia–Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Jl. Sultan Yahya Petra, Kuala Lumpur 54100, Malaysia

*alwatan@polnes.ac.id

Abstract. Recovery of hydrocarbon compounds from waste lubricating oil has gained considerable attention because of its potential as an alternative liquid fuel source and its contribution to environmental protection. Besides containing valuable hydrocarbons, waste lubricating oil also contains sulfur compounds and heavy metals that may reduce fuel quality and cause environmental pollution. This study evaluates the recovery of waste lubricating oil through a pyrolysis–distillation process assisted by activated carbon derived from low-rank coal from East Kalimantan, Indonesia. The activated carbon was synthesized through carbonization and chemical activation and characterized using iodine number analysis to determine its adsorption capability. Response Surface Methodology (RSM) was applied to optimize pyrolysis temperature and activated carbon dosage in order to maximize liquid yield and contaminant removal efficiency. The synthesized activated carbon exhibited an iodine number of 1163.51 mg/g. Optimization predicted optimum conditions at 416.54 °C and 12.87 wt.% activated carbon dosage, producing 89.67% liquid yield and approximately 76% contaminant removal efficiency. Experimental validation confirmed the model prediction, resulting in 88% liquid yield with satisfactory fuel characteristics.

Keywords: activated carbon, RSM, used engine oil

(Received 2026-04-16, Revised 2026-06-18, Accepted 2026-07-10, Available Online by 2026-10-31)

1. Introduction

Used engine oil (UEO) is widely recognized as hazardous waste due to the accumulation of heavy metals (such as Zn, Ca, Fe, and Pb), sulfur compounds, and oxidation by-products generated during prolonged

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engine operation [1]. When disposed of improperly, these contaminants pose serious risks to soil, groundwater, and aquatic ecosystems. At the same time, UEO still contains 70–85% recoverable hydrocarbon fractions, indicating a strong potential for conversion into secondary fuels through appropriate treatment technologies [2]. Consequently, the development of efficient and environmentally friendly UEO recycling technologies has become an important research focus in the context of circular economy and sustainable energy systems. Although pyrolysis and adsorption techniques have been employed in several research to purify and convert old motor oil, their implementation has not been optimal. Because it enables the direct conversion of used engine oil (UEO) into liquid fuels, gases, and solid residues without the need for complicated pretreatment stages, pyrolysis has garnered significant attention among the different recycling techniques available. However, the high temperatures (500–800) °C at which traditional thermal pyrolysis usually operates lead to substantial energy requirements and hastened equipment depreciation. In theory, the UEO pyrolysis process lowers the amount of metal impurities while simultaneously producing light fractions. The effectiveness of Activated Carbon in removing heavy metals from used lubricating oil is well documented. For instance, Activated Carbon derived from palm kernel shells removes approximately 90% of Fe, Pb, and Zn. In related research, coconut shell carbon demonstrated superior Pb adsorption, also reducing Zn levels from 16,475 ppm to 10,375 ppm. Another study reported a decrease of Pb from 181 ppm to 47.56 ppm with Activated Carbon treatment, with Cr rendered undetectable after adsorption. Collectively, these findings indicate that Activated Carbon from biomass can effectively reduce metal contaminants in UEO [3-5].

Numerous studies on the recycling of used engine oil (UEO) have been reported; however, most of them mainly emphasize preliminary adsorption processes employing commercial or biomass-based activated carbon. Meanwhile, the application of low-rank coal-derived activated carbon in an integrated pyrolysis–distillation system has received limited attention. In addition, conventional thermal pyrolysis has not been sufficiently effective in reducing sulfur and metal contents, resulting in liquid products that still require further upgrading before being utilized as fuel [6,7]. Therefore, this study develops an integrated pyrolysis–distillation process assisted by activated carbon derived from low-rank coal from East Kalimantan to enhance liquid fuel yield while simultaneously reducing contaminant levels. The novelty of this work lies in the utilization of underutilized low-rank coal as a value-added precursor for activated carbon, combined with process optimization using Response Surface Methodology (RSM). This approach is expected to provide a more efficient and sustainable conversion process for UEO, while also supporting cleaner fuel production through hazardous waste valorization and more effective utilization of low-rank coal resources.

Activated carbon and biochar have been widely reported to promote cracking reactions and adsorb sulfur- and metal-containing compounds, thereby enhancing liquid fuel yield and reducing contaminant levels during pyrolysis processes [8–10]. Indonesia, particularly East Kalimantan, possesses abundant low-rank coal resources; however, their utilization remains limited due to their high moisture content and low calorific value. Therefore, this study focuses on the development and optimization of a pyrolysis–distillation process assisted by activated carbon derived from low-rank coal, not only to maximize liquid fuel production and reduce sulfur and metal impurities, but also as a preliminary study aimed at increasing the added value of low-rank coal from East Kalimantan as part of coal-based downstream industrial development. Furthermore, Response Surface Methodology (RSM) was employed to systematically evaluate the interaction between operating temperature and activated carbon dosage, which can serve as a reference for determining the optimum conditions in the integrated adsorption–pyrolysis–distillation process.

2. Methods

This study was carried out through several main stages, including the preparation and characterization of activated carbon derived from low-rank coal, the adsorption–pyrolysis–distillation process of used engine oil, and the optimization of operating conditions using Response Surface Methodology (RSM). The experimental procedure was designed to evaluate the effects of operating temperature and activated

carbon dosage on liquid fuel yield enhancement as well as the effectiveness of sulfur and metal contaminant removal.

2.1. Preparation and Characterization of Activated Carbon

Low-rank coal obtained from East Kalimantan was initially crushed using a crusher to obtain smaller particle sizes. The material was then carbonized to remove volatile compounds and increase the fixed carbon content. After the carbonization process, the material was cooled to room temperature, ground, and sieved to pass through a 100-mesh screen in order to obtain a uniform particle size distribution.

After the sieving process, the carbonized material was subjected to both physical and chemical activation to enhance the surface area and develop the pore structure of the activated carbon. Physical activation was carried out through heating at a certain temperature, while chemical activation was performed using activating agents consisting of phosphoric acid and sodium bicarbonate with a composition ratio of 1:1 at a concentration of 2.5 M. The activation process was intended to improve pore development and enhance the adsorption capacity of the material. The overall preparation procedure of activated carbon is presented in Figure 1.

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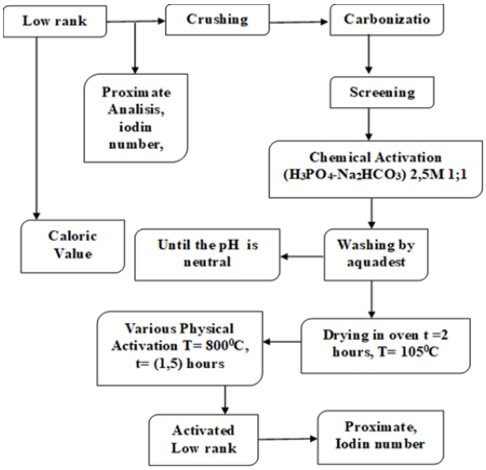


Figure 1. Process Activated Carbon

The produced activated carbon was characterized using proximate analysis, including moisture content, ash content, volatile matter, and fixed carbon, to evaluate the changes in material properties before and after activation.

In addition, the adsorption performance of the activated carbon was evaluated through iodine number analysis based on the Indonesian National Standard (SNI) No. 06-3730-1995. This analysis was conducted to determine the adsorption capacity of activated carbon toward small molecular compounds, which reflects the development of microporous structures in the material. The iodine number was calculated using Equation (1).

$$\text{Number Iodin} = \frac{10 - \frac{(V \times N)}{Niod} x12{,}69 \; x \; fP}{W} \quad \text{.....(1)}$$

A higher iodine number indicates better pore development and greater adsorption capacity of the activated carbon, which is expected to enhance contaminant removal performance during the integrated adsorption–pyrolysis–distillation process.

2.2. Pyrolysis–Distillation Process by RSM Optimization

Used engine oil (UEO) samples were collected from local motorcycle workshops and used as the feedstock in the pyrolysis–distillation experiments. The experiments were carried out using 1500 mL of UEO for each run. The pyrolysis–distillation process was performed by varying two main operating variables, namely operating temperature and activated carbon dosage. The operating temperature ranged from 330 to 470 °C, while the activated carbon dosage varied between 3 and 17 wt.%.

The integrated adsorption–pyrolysis–distillation process was conducted using activated carbon derived from low-rank coal as an adsorbent and cracking-support material. During the process, activated carbon was mixed directly with the UEO feedstock prior to heating. The pyrolysis vapors produced during thermal decomposition were subsequently condensed to obtain liquid fuel products. The experimental setup used in this study is illustrated in Figure 2.

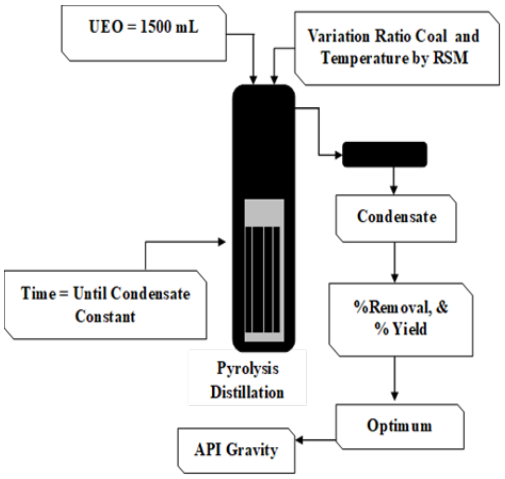


Figure 2. Distillation pyrolysis by RSM

Optimization of the operating conditions was performed using Response Surface Methodology (RSM) with a Central Composite Design (CCD). The RSM design was generated using Design Expert software by selecting the "New Design" menu followed by the Central Composite Design option. This method was applied to evaluate the effects of operating temperature and activated carbon dosage, as well as their interaction, on liquid fuel yield and contaminant removal. The experimental design was generated using Design Expert software with two independent variables were defined in the numerical factor section, namely operating temperature (°C) and activated carbon dosage (%). And the responses evaluated in this study were:

1. Total contaminant removal (%), and
2. Liquid fuel yield (%).

The experimental design matrix generated by RSM is presented in Table 1,

Table 1. Experimental design matrix for pyrolysis–distillation process using RSM

Parameter	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
Temperature (°C)	330	450	400	350	400	470	350	450	400
Ratio AC (%)	10	5	17	15	3	10	5	15	10
Volume UEO	1500 (mL)								
Response 1	Removal (%)								
Response 2	Yield (%)								

The experimental results obtained from each run were statistically analyzed using RSM to evaluate

the interaction between operating temperature and activated carbon dosage, as well as to determine the optimum operating conditions for maximizing liquid fuel yield and contaminant removal efficiency. The optimum conditions predicted by the RSM model were subsequently validated through additional experiments conducted under the recommended operating conditions. The validation experiments were performed to compare the predicted response values with the actual experimental results and to evaluate the reliability and accuracy of the developed model.

3. Results and Discussion

This section presents the experimental results obtained from the preparation of activated carbon and the integrated adsorption–pyrolysis–distillation process of used engine oil (UEO). The discussion focuses on the characteristics of activated carbon derived from low-rank coal, changes in the elemental composition of UEO after the treatment process, and the effects of operating temperature and activated carbon dosage on contaminant removal and liquid fuel yield. In addition, statistical evaluation using Response Surface Methodology (RSM) was conducted to determine the interaction between process variables, identify the optimum operating conditions, and perform repeated validation experiments to verify the accuracy of the RSM predictions.

3.1. Characteristics of Activated Carbon Performance

Based on the research objectives, the analysis was conducted by first determining the composition of activated carbon before and after processing, the results of which are presented in Table 2.

Table 2. Proximate analysis and iodine number of coal before and after activation

No	Parameter	Coal	Activated Carbon	Technical Requirements (SNI No. 06-3730-1995)
1	Moisture	37.72%	4.14%	Maximum 15%
2	Ash	5.49%	16.45%	Maximum 10%
3	Volatile matter content	32.59%	7.46%	Maximum 25%
4	Fixed carbon	24.21%	71.94%	Minimum 65%
5	Iodine Number	103.145 mg/g	1163.513 mg/g	Minimum 750 mg/g

Based on the proximate analysis results presented in Table 2, the activation process significantly improved the characteristics of activated carbon derived from low-rank coal. The moisture content decreased from 37.72% to 4.14%, indicating that the carbonization and activation processes successfully removed most of the water and volatile compounds, which are the primary limitations of low-rank coal. Low moisture content is important for improving thermal stability and maintaining pore accessibility during the adsorption–pyrolysis process [11]. The iodine number increased significantly from 103.145 mg/g to 1163.513 mg/g after activation. This value not only exceeded the minimum requirement of SNI No. 06-3730-1995 (750 mg/g), but also indicated excellent micropore development. Azeez and Ganiyu [12] reported iodine numbers ranging from 820–1050 mg/g for biomass-based activated carbon applied in fuel desulfurization, achieving sulfur removal efficiencies between 60–85%. The iodine number obtained in the present study was higher than those previously reported, suggesting that activated carbon derived from low-rank coal possesses a greater surface area and a higher density of active adsorption sites for contaminant removal.

The findings of this study are also consistent with those reported by Zhang et al. [13], who stated that activated carbon with iodine numbers above 900 mg/g exhibits improved sulfur adsorption due to better pore connectivity and lower diffusion resistance. With an iodine number of 1163.513 mg/g, the activated carbon produced in this study demonstrated superior microporous performance compared with several adsorbents reported in previous studies. This condition contributed to the high sulfur removal efficiency achieved during the integrated adsorption–pyrolysis–distillation process. In addition to the increase in

iodine number, the fixed carbon content increased from 24.21% to 71.94%. This value exceeded the minimum SNI requirement of 65%, indicating that the activation process successfully produced a thermally stable carbon structure. High fixed carbon content is directly associated with the ability of activated carbon to maintain pore structure stability under high-temperature operating conditions [14]. A more stable carbon structure enables the activated carbon to remain effective during the pyrolysis–distillation process.

These results are supported by the findings of Li et al. [15], who reported that activated carbon with fixed carbon content above 65% maintained adsorption performance during waste oil upgrading processes at temperatures up to 450 °C. The fixed carbon value obtained in this study was higher than several biomass-based activated carbons previously reported, indicating that activated carbon derived from low-rank coal possesses better thermal stability for high-temperature pyrolysis applications. However, the ash content increased from 5.49% to 16.45%, exceeding the maximum SNI limit of 10%. This increase was likely caused by residual minerals and activating agents remaining on the activated carbon surface after the activation process. Theoretically, excessive ash content may reduce pore accessibility and decrease adsorption efficiency during long-term application. Nevertheless, in this study, the high ash content did not significantly reduce adsorption performance because the substantial increase in surface area and microporous structure development remained the dominant factors influencing the adsorbent characteristics.

3.2. Distillation pyrolysis process assisted by Activated Carbon Using RSM Optimized

Before the activated carbon-assisted pyrolysis–distillation process using RSM optimization was carried out, the elemental composition of the used engine oil (UEO) was first analyzed. The analysis results showed the presence of sulfur and several metallic contaminants in significant concentrations, as presented in Table 3. Sulfur was identified as the dominant contaminant with a concentration of 3244 ppm, followed by calcium (1220 ppm), zinc (589 ppm), and molybdenum (301 ppm). Smaller amounts of iron, copper, aluminum, lead, silicon, sodium, and magnesium were also detected. The total concentration of metals and sulfur reached 5598 ppm, indicating that the used engine oil contained a substantial amount of contaminants originating from lubricant additives, engine wear particles, and thermal degradation during engine operation. The results of the analysis indicate the presence of several metals and sulfur, as shown in Table 3.

Table 3. Initial elemental composition of the used engine oil sample

Parameter	Initial Content of Used Engine Oil (ppm)
Sulfur (S)	3244
Iron (Fe)	12
Copper (Cu)	9
Aluminium (Al)	11
Lead (Pb)	1
Silicon (Si)	29
Sodium (Na)	9
Molybdenum (Mo)	301
Magnesium (Mg)	173
Calcium (Ca)	1220
Zinc (Zn)	589
Total metals + sulfur	5598

The elemental analysis of used engine oil (Table 3) revealed a high concentration of sulfur (3244 ppm) and significant levels of metallic elements such as Ca, Zn, Mo, and Mg. This composition is consistent with typical used engine oils, where metal-based additives and wear-derived particles accumulate during service life [16]. Nguyen et al. [17] reported sulfur concentrations ranging from (2500 - 4000) ppm in used lubricating oils subjected to pyrolysis upgrading, while total metal concentrations exceeded 5000 ppm, values closely aligned with those observed in the present study. Such high heteroatom and metal contents pose challenges for downstream processing due to catalyst poisoning, corrosion, and deterioration of fuel quality [18].

Once the initial characteristics of the used engine oil were determined, they were used as a reference to evaluate changes in the elemental composition of the oil after the pyrolysis–distillation process assisted by activated carbon. The activated carbon to UEO ratios in 1500 mL were varied temperature according to RSM, and the results are presented in Table 4.

Table 4. Results of the pyrolysis–distillation process based on RSM experiments

RSM Simulation		**Concentration**			
Temperature (°C)	**Activated Carbon–to–UEO ratio (%)**	**Sulfur (ppm)**	**Silica (ppm)**	**Total Removal (%)**	**Yield (%)**
330	10	1323	0.56	59.56	26.18
450	5	680	25	78.46	30.47
400	17	276	16.06	91.08	98.34
350	15	1283	2.57	60.72	72.82
400	3	983	8.4	69.71	49.61
470	10	956	2.57	70.71	98.67
350	5	1367	1.29	58.19	40.59
450	15	999	8.77	69.21	99.77
400	10	875	12.23	72.89	85.25

. The RSM-based experimental results (Table 4), the highest sulfur removal (91.08%) was achieved at 400 °C, with an Activated Carbon-to-oil ratio of 17 %, accompanied by a high yield of 98.34 %. This performance compares favorably with recent studies employing adsorptive upgrading strategies. For instance, Wang et al. [19] reported a maximum sulfur removal of approximately 82 % from pyrolysis oil using activated carbon at 420 °C, albeit with a lower product yield of around 85%. Similarly, Rahman et al. [20] achieved sulfur removal efficiencies of (75 - 88) % using modified activated carbons, but noted significant yield losses at higher adsorbent loadings. The superior performance observed at moderate temperature (≈400 °C) supports findings that excessive temperatures may induce secondary cracking reactions and reduce adsorption efficiency due to desorption or pore degradation [21]. Conversely, temperatures below 350 °C, often result in incomplete volatilization of sulfur-containing compounds, limiting their accessibility to adsorption sites [22]. The effective reduction of sulfur and silica under optimized RSM conditions can be attributed to the combined effects of thermal cracking and adsorption. At optimal temperatures, sulfur-containing compounds are converted into smaller, more mobile species that readily diffuse into the micropores of activated carbon [23]. RSM was employed to evaluate and optimize the performance of the pyrolysis–distillation process in terms of contaminant removal (%) and product yield (%), as summarized in Table 5, and Table 6.

Table 5. RSM model summary for percentage removal response

Source	**Std Dev.**	**R-Squared**	**Adjusted R-Squared**	**Predicted R-Squared**	**PRESS**	**Remark**
Linear	7.52	0.3592	-0.2310	-0.3920	1228.10	
2FI	7.68	0.3985	0.1980	-0.9536	1723.62	

Quadratic	6.17	0.6978	0.4820	-1.1488	1895.77	Suggested
Cubic	3.87	0.91	0.80	-4.43	4794.16	Aliased

Table 6. RSM model summary for percentage yield response

Source	Std Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	Remark
Linear	17.18	0.6471	0.5765	0.3212	5676.86	Suggested
2FI	17.02	0.6882	0.5842	-0.0180	8513.83	
Quadratic	12.86	0.8617	0.7629	0.0163	8227.23	Suggested
Cubic	4.61	0.99	0.97	0.19	6797.78	Aliased

The RSM model summary presented in Table 5 indicates that the quadratic model is the most appropriate model for representing the percentage removal response compared to the linear and 2FI models. The R^2 value of 0.6978 indicates that approximately 69.8% of the variation in removal efficiency can be explained by the process variables and their interactions in the activated carbon-assisted pyrolysis–distillation system. In addition, the ANOVA results demonstrate that the quadratic model has better statistical significance, as indicated by the contribution of the quadratic and interaction terms affecting the removal response. This finding suggests that the contaminant removal mechanism does not follow a simple linear relationship, but is influenced by curvature effects resulting from complex interactions among process parameters.

Although the Predicted R^2 value was found to be negative, this condition is still commonly observed in RSM-based optimization studies involving a limited number of experimental runs and complex reaction systems [24,25]. A negative Predicted R^2 indicates that the predictive capability of the model for new experimental data is relatively lower than its capability to fit the experimental data used for model development. In this study, this phenomenon is likely attributed to the complexity of the simultaneous pyrolysis–adsorption processes, including thermal cracking, volatilization, adsorption, mass transfer limitations, and the possibility of secondary reactions occurring during the distillation process. These interrelated mechanisms may increase experimental variability and consequently affect the predictive performance of the model. Nevertheless, the quadratic model was still selected because it provided better R^2 and adjusted R^2 values compared to the other models and was capable of adequately representing the experimental response trends within the investigated operating range. The superiority of the quadratic model over the linear and 2FI models also confirms that the removal response is strongly influenced by nonlinear interactions between operating temperature and activated carbon ratio. These findings are consistent with previous studies on sulfur and metal removal optimization in pyrolysis-derived oils, where quadratic terms played a significant role in accurately describing removal behavior [26,27]. Furthermore, the results presented in Table 6 show that the percentage yield response is also best represented by the quadratic model, with R^2 and adjusted R^2 values of 0.8617 and 0.7629, respectively. These values indicate a strong relationship between the process variables and the liquid distillation yield. Based on the ANOVA results, the yield model also demonstrated good statistical significance, indicating that the model is sufficiently representative for describing the effects of temperature and activated carbon ratio on liquid product distribution.

In pyrolysis–distillation systems, operating temperature is one of the main parameters controlling liquid product formation. Moderate temperatures generally enhance liquid yield because devolatilization occurs more effectively, whereas excessively high temperatures promote secondary cracking reactions that increase gas formation [28]. In addition, activated carbon not only acts as an adsorbent for sulfur and metal removal, but also affects vapor composition, residence time, and hydrocarbon stability prior to condensation [29]. Therefore, the interaction between temperature and activated carbon ratio results in nonlinear response behavior for both removal efficiency and liquid yield.

In general, increasing the activated carbon ratio tends to improve removal efficiency because a larger adsorbent surface area enhances contaminant adsorption capacity. Under certain operating temperatures,

improved removal performance may also contribute to higher liquid yield due to the reduction of impurities and the improvement of condensable hydrocarbon fractions. However, excessively high temperatures, although capable of increasing yield through intensified cracking and volatilization processes, may reduce removal efficiency because the adsorption effectiveness of activated carbon decreases at elevated temperatures. The relationships between temperature, activated carbon ratio, removal efficiency, and yield are illustrated in Figures 3, 4, and 5.

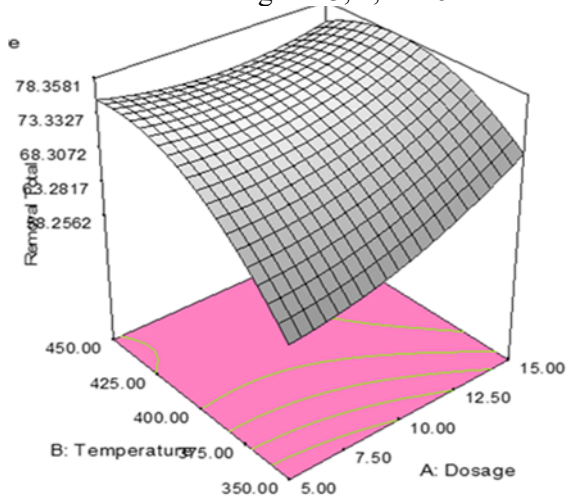


Figure 3. 3D plot showing the effect of temperature and Activated Carbon dosage on removal efficiency

Figure 3 illustrates the combined influence of pyrolysis–distillation temperature (B) and activated carbon dosage (A) on the removal efficiency Response. The curved surface indicates a nonlinear interaction between the two variables, where removal efficiency increases with temperature and adsorbent dosage up to an optimum region before declining. This behavior confirms that the removal process is governed by coupled thermal effects and adsorption mechanisms, which are effectively captured by the quadratic RSM model.

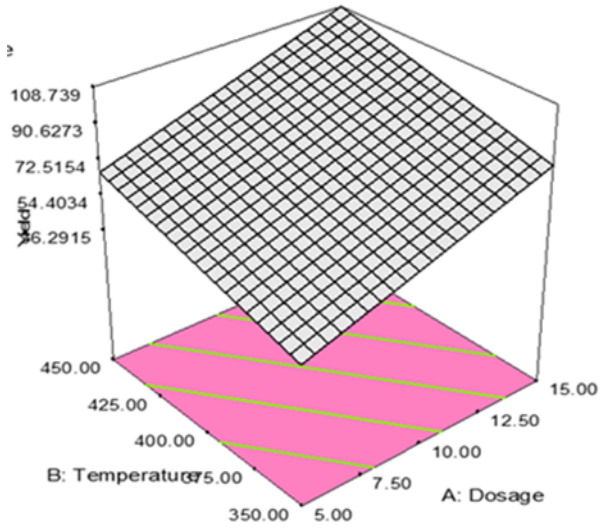


Figure 4. 3D RSM plot showing the effect of Activated Carbon dosage and temperature on distillation yield

Figure 4 illustrates the three-dimensional Response surface generated from the RSM analysis, depicting the combined influence of activated carbon dosage (A) and operating temperature (B) on the distillation yield during the pyrolysis–distillation process. The plot illustrates the combined influence of temperature and Activated Carbon dosage on liquid yield, highlighting a nonlinear interaction where optimal yield is achieved at intermediate operating conditions.

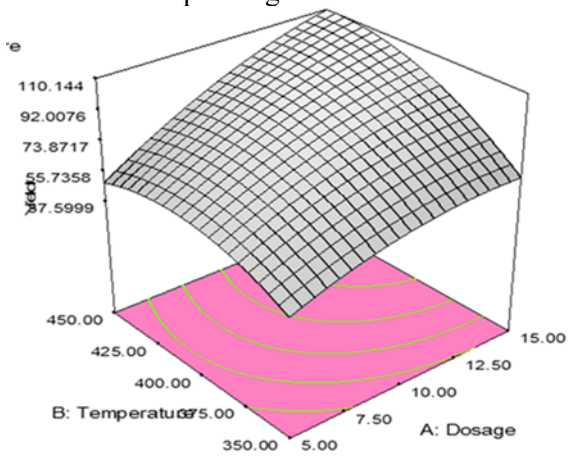


Figure 5. 3D RSM plot of yield as a function of temperature and Activated Carbon dosage

This figure illustrates the combined effect of activated carbon dosage and pyrolysis–distillation temperature on liquid yield. The curved surface indicates a nonlinear interaction, where moderate temperatures and appropriate adsorbent dosage favor higher yield, while excessive severity may reduce liquid production due to secondary cracking. This trend is consistent with Table 7, which shows that the optimal combination of activated carbon dosage and pyrolysis–distillation temperature predicted by RSM results.

Table 7. Optimization and desirability values obtained by RSM

Run	Dosage (%)	Temperature (°C)	Yield (%)	Total Removal (%)	Desirability	Remark
1	12.87	416.54	89.68	76.00	1.000	**Selected**
2	12.29	402.52	83.03	74.90	1.000	—
3	9.19	416.06	73.86	73.86	1.000	—

The RSM optimization results indicate that all selected operating conditions achieved a desirability value of 1.000, confirming an optimal balance between yield and total contaminant removal. The selected condition (Run 1), with an Activated Carbon dosage of 12.87 % and a temperature of 416.54 °C, provided the highest yield 89.68 % while maintaining a high removal efficiency 76.00 %. These results demonstrate that moderate-to-high temperatures combined with sufficient activated carbon dosage favor simultaneous maximization of distillation yield and contaminant removal in the pyrolysis–distillation process.

Based on the optimal RSM recommendation (first-ranked solution), a validation experiment was conducted. The experimental results yielded a product yield of 88% with a total metal removal efficiency of 77.50 %, showing good agreement with the RSM predictions. The distilled oil exhibited an API gravity of 47.66 °API, indicating a light hydrocarbon fraction. According to standard petroleum classification, fuels with API gravity above 40 °API are generally categorized as light distillates, such as kerosene or jet fuel, whereas conventional diesel fuels typically fall within the range of (30 - 38) °API [30,31]. Therefore, the obtained product can be classified as kerosene-like fuel rather than diesel. The high API gravity achieved confirms the effectiveness of the activated carbon-assisted pyrolysis–distillation process in promoting cracking of heavy hydrocarbons and removing metal contaminants,

resulting in lighter and higher-quality fuel fractions. Similar findings have been reported in recent studies on waste oil upgrading via pyrolysis and catalytic or adsorptive distillation, where optimized operating conditions led to products within the kerosene/jet fuel range with improved physicochemical properties [32–35]. These results demonstrate that the proposed process is technically promising for producing light distillate fuels from used engine oil.

4. Conclusion

Activated Carbon derived from low-rank coal demonstrated strong effectiveness as an adsorbent–carbon catalyst in the pyrolysis–distillation of used engine oil. Response Surface Methodology (RSM) successfully identified optimal operating conditions, resulting in a high liquid yield is 88 % and substantial contaminant removal is 77.5 %. The validated experimental results showed good agreement with RSM predictions, confirming the robustness of the developed models. The upgraded product exhibited an API gravity of 47.66 °API, indicating kerosene-range fuel characteristics. These findings highlight the technical feasibility of integrating Activated Carbon and RSM optimization for efficient waste oil upgrading and value-added utilization of low-rank coal.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT (OpenAI) to support English editing and improve the clarity of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgements

The authors would like to thank the Center for Research and Community Service (P3M) of Samarinda State Polytechnic (POLNES) for funding this research, the Department of Chemical Engineering POLNES for providing laboratory facilities, and Universiti Teknologi Malaysia for their consultation in the preparation of this article.

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