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RESEARCH ARTICLE

Optimization of Aceh Low Rank Coal Upgrading Process with Combination of Heating Media to Reduce Water Content through Response Surface Method

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Abstract

This research aims to improve the rank of coal in Aceh, which is known to have a relatively high moisture content of 44-52%. The upgrading process is carried out by using hot water, and hot oil as media combined with microwaves to remove moisture content in coal. The process was carried out using microwave rotary dryer equipment by varying the coal particle size of 10, 20, and 30 mesh, and the time for 20, 40, and 60 minutes. Response surface methodology utilizing the Central Composite Design (CCD) approach was employed to ascertain the optimal conditions for low rank coal, culminating in nine experimental runs involving low rank coal. The validation of the derived quadratic polynomial model has been conducted, yielding a correlation coefficient (R^2) value of 0.994. The optimization process aimed at maximizing the moisture content of low rank coal at 4.906 kg, which resulted in a 20% reduction by adjusting the particle size to 5 Mesh M and the duration to 20 minutes, respectively. Consequently, this research is anticipated to serve as a foundational reference for the advancement of coal upgrading methodologies in Aceh, facilitating their transition from laboratory scale to commercial implementation.

Keywords: Low Rank Coal (LRC) ; Coal Upgrading ; Moisture Content ; Optimization.

1. Introduction

The coal potential in Indonesia is 85% lignite coal. Aceh is recognized for possessing substantial resources in the mineral extraction sector, particularly coal. According to Wattimena et al (Wattimena et al., 2019), in West Aceh, approximately 500 million tons of coal reserves are classified as lignite (Rajagukguk and Jati, 2018), thus necessitating a process of enhancement or elevation of this lignite coal to medium-rank or high-rank coal (Al Tuffahati et al., 2023; Fatia Umar et al., 2024). This would consequently augment the economic value of coal and optimize its application in the industrial sector (Jannah and Junaidi, 2023).

The upgrading of low-rank coal is typically conducted to diminish moisture content (Sun et al., 2019), volatile matter content, low oxidation temperature (Rahmawati et al., 2018), and spontaneous ignition during transit and storage, thereby augmenting the calorific value of the coal (Huang et al., 2022; Mergalimova et al., 2024; Zhang et al., 2022). From the examination of coal quality parameters in the Meulaboh Basin undertaken by Hanum et al, representative low-rank coal data on an as received (ar) basis for moisture content is acquired in the range of 44-52%, which constitutes a comparatively elevated percentage (Hanum et al., 2024). Consequently, this investigation was performed to reduce the moisture content of low-rank coal in Aceh and to compute the calorific value of coal subsequent to the enhancement process, while also contrasting several upgrading methodologies employing diverse techniques so that they can serve as a reference in the advancement of a more cost-effective upgrading process for the sustainability of coal utilization in the future (Pratama et al., 2022; Putri, 2023).

Within the low-rank coal enhancement procedure, various methodologies have been devised. Various techniques to increase the calorific value of low-rank coal by eliminating moisture content have been devised. Some of the techniques employed encompass the utilization of heated air, hot oil (Ohm et al., 2012), and superheated vapor (Pusat et al., 2016) as desiccating mediums. Nevertheless, traditional heating techniques are less efficacious in terms of temporal and energetic demands. This is attributable to the fact that the thermal flux in conventional desiccation systems progresses from the particle surface to the core of the particle, whereas the moisture mass flux transitions from the interior to the particle surface. Among the traditional methods that have been developed, there exists a novel innovation that is implemented, specifically through the utilization of microwaves. Microwaves emit electromagnetic radiation with a frequency spanning from 300 MHz to 300 GHz or a wavelength of 1 to 300 mm. The energy released from microwaves to coal will induce friction within the coal, generating heat that facilitates the evaporation of water from the coal (Sardi et al., 2023).

In this research, low rank coal obtained from Aceh was employed as the raw material for the pyrolysis process, while the operational parameters were refined through the application of Design Expert software. Consequently, the principal objective of this research was to enhance the pyrolysis efficiency of the substandard coal from Aceh by utilizing the response surface methodology (RSM). The Design Expert software was utilized to develop the central composite design (CCD) experimental configuration and to ascertain the optimal operational conditions. The statistical relationships among various parameters, such as sample size and retention time in relation to moisture content, were meticulously examined. The moisture content of the pyrolysis products derived from the inferior coal sourced from Aceh, influenced by a range of heating mediums, was determined to be significantly contingent on sample size and retention time.

2. Methodology

This research was undertaken at the Energy and Resources Laboratory, Department of Chemical Engineering, Syiah Kuala University and the Mechanical Engineering Laboratory, Abulyatama University. Proximate Analyses for low rank coal can be elucidated in table 1. Low rank coal specimens were triturated utilizing an iron mortar. The specimens were first obtained on a series of sieves, with mesh sizes of 10, 20 and 30 mesh then washed through Washing action for normal preparation (WANAP). Also, 100 g of crushed coal is exposed to the oven at 4 h with 100 °C and weighted for moisture content before the upgrading process.

Table 1. Characteristics of low rank coal Aceh

Coal Sample	Moisture content (%)	Volatile Matter (%)	Ash (%)	Sulfur (%)	Calorific Value (kkal/kg)
Subbituminous	45	39	2	0.2	3400-4200

2.1 Equipment and Material.

The equipment used in this research includes a microwave-stirred dryer (Fig. 1), bomb calorimeter, oven, analytical balance, 10 kg bench scale, iron mortar, and mechanical sieves with 5, 10, and 15 mesh sizes. The materials used in the study are low-rank coal samples, water, used oil, and aluminum foil

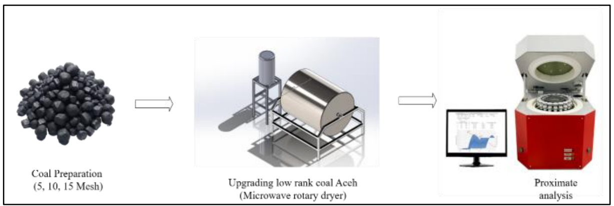

Fig 1 . Experiment procedure

2.2 Experimental Design

To optimize moisture removal during the pyrolysis of low-rank Aceh coal, we used Response Surface Methodology (RSM) (Hernomita and Erfando, 2023). This statistical technique helped us analyze the relationship between moisture content and factors like sample mass and residence time . By applying RSM, we aimed to determine the ideal combination of these factors to achieve the lowest possible moisture content and understand the curvature of the response surfaces [32]. The software Design Expert (Version 13) offered two configurations for response surface methodology: Central Composite Designs (CCDs) and Box-Behnken designs, with CCD being identified as the most suitable option. The Central Composite Design was adept at accommodating both first-order (linear) and second-order (quadratic) models, utilizing axial and central points as part of its framework. Additionally, design characteristics such as orthogonality, curvature, and rotatability were systematically assessed through the use of CCD.

Optimization of the process was performed using a central composite design (CCD). This design had a two-level factorial design with center point experiments, axial points. This Design of experiments gave nine of experimental runs, 32d using six (m=6) center points replicate three times and six axial points. Axial points were situated at α distance from the center, with α > 1. The CCD was applied in multiple blocks to make orthogonal and get rid of covariance between regression coefficients. The model enabled to estimate block and factor effects separately. Equally spaced tagging was used to calculate N, the total number of experiments (Equation 1, where n = the number of factors).

$$N = 2^n + 2n + m = 2^2 + 2.2 + 1 = 9 \quad (1)$$

Pyrolysis of Low rank coal Aceh for coal pre-treatment with low moisture content with the sample size 5 to 15 mesh, the residence time from 20 to 60 minutes. 2.3 CCD design and analysis A central composite design (CCD) was assigned using Design Expert software. Each factor had high (+1), low (-1), and centre points (0) and two outer points (±1.414) in CCD. Table 2: Coded and actual levels of the experimental variables, Table 2. summarizing the coded and experimental variables for CCD Low rank coal aceh pyrolysis data set, as a function of variances, appears in a composite overlay plot presented at Table 3.

The data was subjected to statistical analysis, regression modelling, ANOVA and response surfaces & contour plots using Design Expert 13 software. P values <0.0001 were considered to exhibit a significant difference between treatments. The conditions (particle size A, time B) were determined statistically Optimal. The Design Expert software was also employed to fit the developed equations and generate response surfaces and contour plots.

Table 2. Coded and Experimental Variables for CCD

Coded Variable	Experiment Variable	Coded level and actual Level				
Hot Water and Hot Oil		-α	-1	0	+1	+α
A	Particle size (Mesh)	2.928	5	10	15	17.071
B	Time (minute)	11.716	20	40	60	68.284

Table 3. CCD run order and response for hot oil and hot water of low rank coal

Std	Run	Particle Size (Mesh)	Time (min)	Moisture Content/weight (Kg)	
				Hot Water	Hot Oil
2	1	5	20	5.22	5.19
1	2	5	40	5.15	4,93
3	3	5	60	4.93	4,8
6	4	10	20	5.22	5,17
7	5	10	40	5.1	4,86
8	6	10	60	4.91	4,77
4	7	15	20	5.24	5,12
5	8	15	40	5.07	4,84
9	9	15	60	4.89	4,73

3. Results and Discussion

3.1 Experimental Design

The comparison between the hot water and hot oil methods can be seen from the percentage of degree of dewatering which states the percentage of water that can be removed during the process. The calculation of the degree of dewatering can be done using the following formula (Prakoso et al., 2022; Yuliansyah et al., 2020).

$$Degree\ of\ Dewatering = \frac{M_{Raw\ Coal} - M_{Upgraded\ Coal}}{M_{Raw\ Coal}}\ x\ 100\% \quad (2)$$

In Figure 2, the hot oil method gives a higher percentage than the hot water method. This is because the oil is able to press and coat the coal part which causes the coal to become hydrophobic, thus preventing water from being reabsorbed (Tamara et al., 2019). The percentage of degree of dewatering obtained in the hot water method with a particle size of 5 <10 <15 mesh is 0.014; 0.018; and 0.022%, respectively. While in the hot oil method with the same particle size, respectively, it is 0.04; 0.046; and 0.054%.

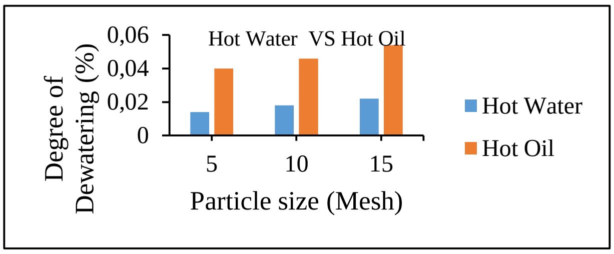

Fig 2 . Comparison of Coal Upgrading Results from Variations of Hot Water and Hot Oil Methods

3.2 Stastical Regression Analysis

The models, delineating the influence of various parameters on the moisture content indices of low rank coal from Aceh, are illustrated in Table 4. Equation (3-6) quantitatively depicts the fluctuations in the moisture content of the low rank coal from Aceh as influenced by the alterations in particle size (A) and time (B) (Raharjo et al., 2022). The Model F-value of 81.39 implies the model is significantThere exists merely a 0.01% probability that an F-value of this magnitude could transpire as a result of random variation. P-values inferior to 0.0500 signify that the model parameters are statistically significant. In this scenario, tim (B) constitutes a significant model parameter. Values exceeding 0.1000 denote that the model parameters are not statistically significant. Should there be a multitude of insignificant model parameters (excluding those necessary to uphold hierarchical structure), model reduction may enhance your model. The Predicted R^2 of 0.9170 is in reasonable concordance with the Adjusted R^2 of 0.9526; that is, the disparity is less than 0.2.

The ANOVA findings, consequently, statistically validate the framework to depict the influence of various factors on the moisture content of the low rank coal in Aceh. Likewise, the ANOVA evaluations of the models formulated to quantitatively elucidate the impacts of particle dimensions and duration on moisture content are statistically significant with acceptable regression coefficients and sufficient precision values as demonstrated in Table 4.

Table 4. Analysis of variance (ANOVA)

Source	SS	DF	MS	F-Value	Prob>F
Hot Water					
Model	0.1521	2	0.0760	81.39	<0.0001 (Significant)
A-Particle Size	0.0017	1	0.0017	1.78	0.2301
B-Time	0.1504	1	0.00154	161.00	<0.0001
Residual	0.0056	6	0.0009		
Hot Oil					
Model	0.2559	5	0.0512	215.93	0.0005 (Significant)
A-Particle Size	0.0088	1	0.0088	37.20	0.0089
B-Time	0.2321	1	0.2321	979.03	<0.0001
AB	0.0000	1	0.0000	0.0000	1.000
A2	5.556 x 10-6	1	5.556 x 10-6	0.0234	0.8880
B2	0.0150	1	0.0150	63.37	0.0041
Residual	0.0007	3	0.0002		

Table 5. Models Representing Moisture Content Analysis of Low Grade Coal

Response	Model	Coded/Actual	Eq.
Moisture Content Hot Water	5.08 – 0.0167A – 0.1583B	Coded	(3)
	5.4311 – 0.00333A – 0.007917B	Actual	(4)
Moisture Content Hot Oil	4.88 – 0.0383A – 0.1967B + 0.0017A2 + 0.0867B2	Coded	(5)
	5.69 – 0.009A – 0.0217B + 2.51 x 10-8 + 0.000067A2 + 0.000217B2	Actual	(6)

The mathematical representation in terms of encoded variables can be utilized to formulate forecasts regarding the outcome for specified magnitudes of each variable. By convention, the elevated magnitudes of the variables are encoded as +1 and the diminished magnitudes are encoded as -1. The encoded mathematical representation is advantageous for discerning the comparative influence of the variables through an analysis of the variable coefficients (Sen and Sen, 2023). The mathematical representation in terms of actual variables can be employed to formulate forecasts regarding the outcome for specified magnitudes of each variable. Herein, the magnitudes ought to be delineated in the original units for each variable. This representation should not be employed to ascertain the comparative influence of each variable due to the coefficients being normalized to accommodate the units of each variable and the intercept not being positioned at the centroid of the design space (Putra et al., 2023). Fig. 3 illustrates the distribution of experimental vs model predicted moisture content distributed around perfect prediction line (dotted line, RSM = experimental).

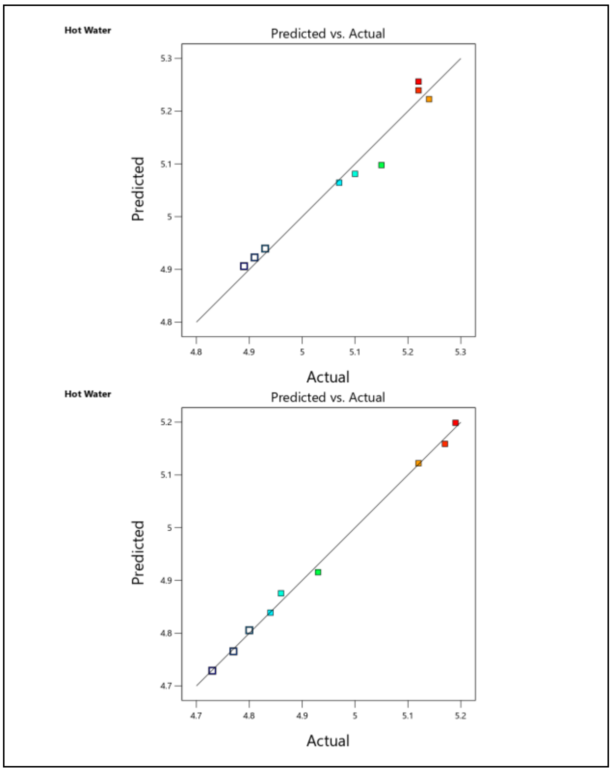

Fig 3 . Experimental vs RSM model predicted values of moisture content. The dotted lines (RSM = Experimental) pass from the origin and represent the perfect prediction.

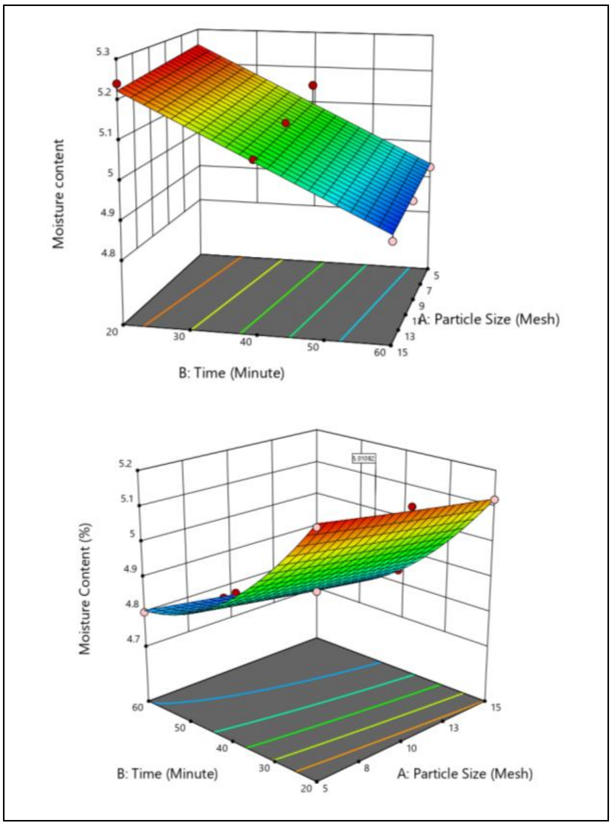

Fig 4 . The moisture content response surface contour and 3-D plots for the effect size particle (mesh) and time (min) on low rank coal Aceh

3.3 Factor Variations and Effect on Low Rank Coal Aceh Model

By examining contour and response surface plots, we visualized how factors like particle size, moisture level, and retention duration influenced the slow pyrolysis process of low-quality Aceh coal. Our 3D plots revealed patterns in these interactions, confirming that larger particles can enhance heat transfer and drying efficiency (Rahmad et al., 2022). As shown in Figure 4, reducing retention time for larger particles or extending retention time for smaller particles both led to effective moisture removal (Deng et al., 2021; Rego et al., 2022). These findings suggest that carefully optimizing these parameters can significantly improve the overall efficiency of the pyrolysis process (Wang et al., 2024).

3.4 Optimization Analysis

Using Design Expert software, we determined the optimal settings for particle size and retention duration to minimize moisture content in low-rank Aceh coal during pyrolysis. Figure 5 illustrates the global solutions, showing that the ideal conditions vary depending on the heating medium. To validate these findings, we conducted confirmatory experiments using the optimal settings. As predicted by the software, the lowest moisture content (4.906% in hot water and 4.729% in hot oil) was achieved with 15-mesh particles and a 60-minute retention time. The experimental results closely matched the model predictions, confirming the accuracy and reliability of our optimization approach.

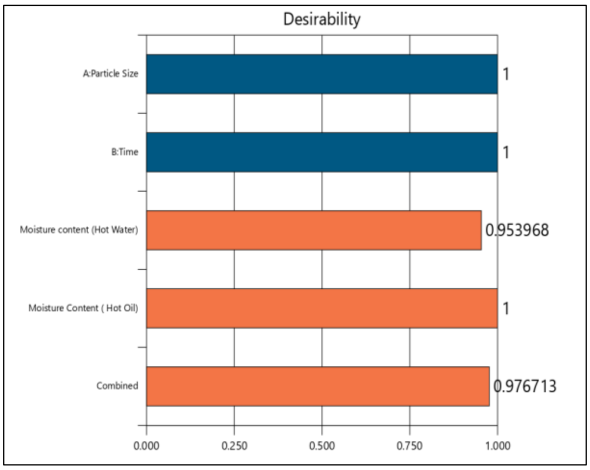

Fig 5. Response Optimization Parameters for low rank coal Aceh

4. Conclusion

Response surface methodology (RSM) constitutes an advantageous instrument for modeling, upscalling and optimizing the alteration in the moisture content of low-rank coal from Aceh in relation to variations in particle size and duration. It was noted that the moisture content of the low-grade coal from Aceh exhibits significant fluctuations with respect to the diverse variables, including particle size and duration. The moisture content of the low rank coal increased from 5 to 4.906 in hot water and 4.729 in hot oil (%). The upgrading process that has been developed has been able to reduce the water content contained in low-rank coal, although not significantly. However, this study is the basis for determining further variables for further Research.

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