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RSM-optimized biochar production from young coconut waste (*Cocos nucifera*): Multivariate analysis of non-linear interactions between temperature, time, and activator concentration

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A B S T R A C T

Organic waste, particularly from young coconut husks, comprises over 60 % of landfill material, presenting significant environmental challenges. This study presents a biochar production method that integrates Response Surface Methodology (RSM) to optimize the carbonization process. The optimization framework uncovers non-linear interactions between carbonization temperature, duration, and KOH concentration, improving prediction accuracy. Carbonization temperature emerged as the most influential factor, with the optimal conditions, 400°C, 165.8 min, and 4.07 M KOH, yielding biochar with an iodine number of 1398.2 mg/g and an MB adsorption efficiency of 93.9 %. The enhanced model achieved an attractiveness index of 90.2 %, a significant improvement compared to conventional methods (84.5 %). Validation experiments confirmed the model's precision, with actual results closely matching predictions: a biochar yield of 25.7 %, an iodine number of 1395.7 mg/g, and MB adsorption of 94.3 %, all within a variance of less than 2 %. This represents a nearly identical iodine number, with only a 0.2 % difference, and a 6.3 % improvement in MB adsorption capacity compared to commercial biochar. This approach significantly advances biochar production from young coconut waste and expands its applications in sustainable waste management.

1. Introduction

The escalating global waste crisis necessitates the development of innovative and sustainable waste management solutions. Organic waste constitutes a significant portion of municipal solid waste (50–60 %), presenting substantial environmental challenges due to its decomposition, which generates greenhouse gases and leachates (Pour and Makkawi, 2021). With global coconut production exceeding 62 million tons annually, especially in tropical regions like Papua New Guinea, Indonesia, Malaysia, and the Philippines (Stelte et al., 2022), coconut waste significantly contributes to solid waste accumulation (James and Yadav, 2021). The Food and Agriculture Organization's 2020 statistics indicate that the annual global output of coconut waste is approximately 61.5 million tons, with a projected annual growth rate of 1 % (FAO, 2020).

Recent research has increasingly focused on converting organic waste into valuable resources, with biochar emerging as a particularly promising solution. Produced through controlled pyrolysis of biomass, biochar is notable for its high carbon content and exceptional properties, including a surface area of 100–1000 m^2/g and a highly porous structure. These characteristics make biochar highly effective for soil amendment, carbon sequestration, and environmental remediation

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(Samsudin et al., 2022). The effectiveness of biochar as a natural adsorbent has been extensively documented, with studies demonstrating its capacity to adsorb a wide range of pollutants. For instance, biochar has shown remarkable adsorption capacities, reaching up to 500 mg/g for contaminants such as heavy metals, herbicides, synthetic dyes, and antibiotics (Zakaria et al., 2023).

The carbonization process, a crucial step in biochar production, involves pyrolyzing biomass at temperatures ranging from 300 to 800°C. The duration and temperature of the pyrolysis are key factors influencing the composition of the final product (Ahmad Farid et al., 2020). Brief pyrolysis durations, such as 30 min, primarily produce volatile organic compounds that condense into bio-oil. In contrast, extended pyrolysis times, exceeding 60 min, favor the formation of solid biochar characterized by enhanced structural stability and higher carbon content (Zhu et al., 2019). Additionally, higher pyrolysis temperatures, particularly those above 700°C, induce thermal cracking of biomass components, resulting in the generation of gases like CO and CO_2, as well as byproducts such as tar (Glushkov et al., 2021).

To enhance the adsorption properties of biochar, chemical activation is typically conducted at temperatures between 400 and 600℃, using activating agents such as phosphoric acid (H_3PO_4) or potassium hydroxide (KOH) (Ahmad Farid et al., 2021). This process not only introduces functional groups that improve biochar's chemical affinity for contaminants but also significantly enhances its pore structure and specific surface area, reaching values between 300 and 1000 m^2/g (Zakaria et al., 2023). By creating additional micropores and mesopores, chemical activation enables biochar to achieve higher adsorption capacity and greater contaminant attraction (Ng et al., 2022; Tomczyk et al., 2023; Yang et al., 2019). Typically, the process involves impregnating biochar with the activating agent, followed by controlled heating and dehydration, which results in a biochar structure optimized for effective adsorption.

Response Surface Methodology (RSM) is a statistical tool commonly used to optimize complex, multivariable processes, as seen in recent studies on biochar production (Yameen et al., 2024). These studies have highlighted RSM's ability to uncover non-linear interactions between factors, making it an ideal approach for optimizing biochar production parameters such as temperature, duration, and activator concentration. Given the complex interactions between these production variables, achieving optimal biochar characteristics requires an effective method to navigate these multivariate factors. Response Surface Methodology (RSM) is an ideal approach, offering a structured, non-linear statistical technique to model and optimize processes that involve multiple, interdependent variables. By applying RSM, researchers can explore and fine-tune the influence of temperature, pyrolysis time, and activating agent concentration to enhance biochar's adsorption efficiency systematically (Promraksa and Rakmak, 2020).

In this study, we employ RSM to optimize the biochar production process for coconut waste, integrating high-temperature pyrolysis with chemical activation to maximize biochar's adsorption performance. This optimized process aims to transform coconut waste into a valuable resource for environmental remediation, addressing pressing waste management challenges and advancing sustainable environmental solutions.

2. Methodology

2.1. Materials

Young coconut waste (*Cocos nucifera*) was procured from the Sri Serdang Wet Market located in Selangor, Malaysia. Potassium hydroxide (KOH, 95.5 %), hydrochloric acid (HCl, 37 %), sodium thiosulfate ($Na_2S_2O_3$, 99 %), iodine (I2, 99 %), sodium iodide (NaI, 99 %), and a starch solution (~1 % w/v) were obtained from Sigma-Aldrich, USA.

2.2. Central Composite Design (CCD)

It is common practice to use the Central Composite Design (CCD) method when mathematically modeling biological and chemical processes (Zhou et al., 2020). By carefully analyzing the response surface via a sequence of carefully selected experimental trials, the goal is to ascertain the ideal circumstances for a certain process. The goal of this study is to establish which elements have the most influence on a predetermined response, create a model to explain how these factors relate to responses, and then choose the best possible conditions for the response (Fig. 1).

A base level (-1), a middle level (0), and an upper level (+1) are the three levels of the factors that are first established in the experimental design. The design matrix for the experiment is generated using CCD, which involves a combination of factorial, axial, and center point trials. Subsequently, the design matrix is revised by including the observed response characteristics. The experimental data is examined using analysis of variance (ANOVA) in combination with relevant diagnostics. The optimization findings are then shown graphically via the use of contour or 3D surface plots.

Table 1 displays the ranges for the three variables. The axial value (A) is determined by the formula $A = 2k/4$, where k is the number of components. The value of α is encoded as 1.68179 (2)/4 when k is equal to 3. After establishing the proportionality using the original variables, the factor levels in terms of uncoded α and $-\alpha$ values may be further determined. The experimental data was analyzed using a second-degree model equation, as shown in Eq. 1. Here, 'n' stands for the overall number of trials in the experiment, and 'Y' is the predicted outcome. Each of the coefficients for the constant, linear, quadratic, and interaction term regression are represented by the symbols βo, βi, βii, and βij, respectively. With the use of Design-Expert 13 software, we performed ANOVA and regression analysis with a 95 % confidence level to evaluate the regression model's fitness.

$$Y = \beta o + \sum_{i=1}^{n} \beta iXi + \sum_{i=1}^{n} \beta iiXi^2 + \sum_{i=1}^{n}\sum_{i>1}^{n} BijXiXj \quad (1)$$

2.3. Activated biochar production

Biochar production methods were revised in light of the approaches described in works by Qi et al. (Qi et al., 2023) and Hoc Thang et al. (Hoc Thang et al., 2021). At first, the raw material was subjected to cleaning with distilled water and then shredded into proportions measuring

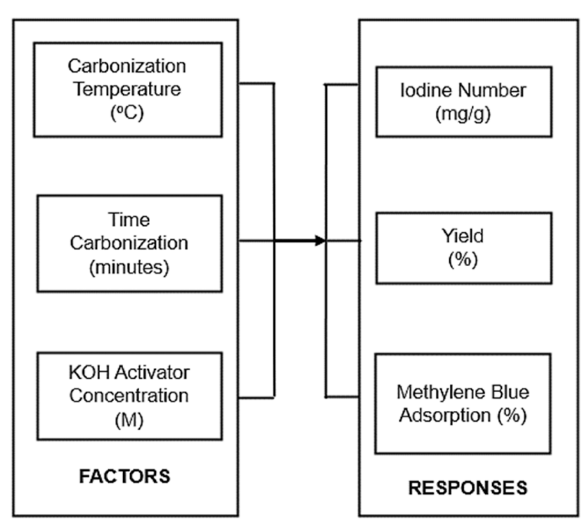

Fig. 1. Factors and responses considered for optimizing biochar production from young coconut waste.

Table 1
Specific ranges for the three variables optimized in this study.

Code	Factors	Units	Design points			Reference
			-α	0	+α	
A	Carbonization temperature	°C	400	500	600	(Zhang et al., 2022)
B	Carbonization time	min	90	145	200	(Chen et al., 2020)
C	KOH concentration	M	2	3,5	5	(Aryani, 2019)

3–4 cm in length, breadth, and height. Subsequently, the specimens were dehydrated to maintain a moisture content ranging from 5 % to 15 %. A dried young coconut weighing 600 g was placed into the reactor in an oxygen-restricted atmosphere. The reactor was initially intended to use steam for activation. However, to simplify the carbonization process for the sake of this study, the steam activation feature was disabled, as shown in Fig. 2. The heating rate used was 25°C per min, while the pyrolysis durations ranged from 90 to 300 min and the temperatures ranged from 400 to 600°C. After obtaining the biochar, it was subjected to three washes using a water-to-biochar ratio of 3:1 to remove soluble contaminants. Subsequently, it was dried at a temperature of 105℃.

With minor adjustments, this study's experimental strategy was based on the methodologies outlined by Lü et al. (Lü et al., 2022) and Herath et al. (Herath et al., 2021). The chemical modification process included treating the biochar with KOH at concentrations ranging from 2 to 5 M (with a water-to-biochar ratio of 3:1). After that, the biochar was soaked for 24 h and dehydrated at 70°C for 72 h. Following pH adjustment using a 0.1 M HCl solution, the dehydrated biochar was then neutralized using distilled water.

2.4. Biochar characterization

Iodine number (mg/g), yield (wt%), and methylene blue (MB) adsorption (%) were among the several response analyses performed in this study. Eq. 2 shows the results of the gravimetric method, which was used to determine the yield (Zhu et al., 2019). The adsorption capability of activated biochar was assessed by determining its iodine number, following the procedure outlined in ASTM D4607–94 (Nunes and Guerreiro, 2011). This standard method measures the iodine adsorption capacity, serving as an indicator of the surface area and microporosity of the biochar, which are key factors in its overall adsorption performance. Eq. 3 shows the formula for calculating the iodine number. N_1, V_1, H_1, F_1, S_1, M_C, and S_2 are all volumes that represent different quantities in this equation: N_1, the volume of iodine solution added, V_1, the volume of iodine solution added, the volume of 5 % HCl added, the volume of filtrate used in the titration, the volume of $Na_2S_2O_3$ solution consumed, and the mass of activated carbon.

As an indicator of its mesoporous character, MB experiments were used to evaluate the interaction between biochar and organic compounds. Fifteen mg of MB dissolved in one liter of pH 7 deionized water (dH_2O) made up the solution with adsorbent utilized had a concentration of about 0.4 g/L (Loulidi et al., 2023; Tafvizi et al., 2021). After 30 min of adsorption at 150 rpm and room temperature, the spent adsorbent was removed by centrifugation at 3000 rpm. A 660 nm wavelength was used to measure the initial and equilibrium concentrations of MB using a UV-Vis spectrometer (Thermo Scientific Genesys 30). The effectiveness of MB removal was measured using Eq. 4, where *Co* and *Ce* are the initial and equilibrium concentrations of MB (mg/L), respectively.

$$Biochar\ yield(\%) = \frac{Final\ weight\ biochar\ produced}{Initial\ weight\ biomass} \times 100\% \tag{2}$$

$$Iodine\ number(mg/g) = \left\{(N_1 \times 126.93 \times V_1) - (\frac{V_1 + H_1}{F_1}) \times (S_1 \times 126.93) \times S_2\right\} / M_c \tag{3}$$

$$MB\ adsorption(\%) = \frac{Co - Ce}{Co}\ x\ 100\% \tag{4}$$

3. Results and discussion

3.1. Regression model analysis

The yield and iodine number are greatly affected by the appropriate conditions for biochar formation, as shown by the CCD studies. According to Yang et al. (2017), yield testing is a measure of the proportion of raw resources that are converted into final products. Higher yields suggest increased productivity. The iodine number test, as outlined by Herath et al. (2021), assesses the porosity of biochar, particularly in the region including macropores; a higher result indicates the existence of bigger macropores. Similarly, the MB test evaluates the pore characteristics of biochar, with a special emphasis on the mesopore size range. Higher removal values imply a larger abundance of mesopores, which aligns with the findings of Lü et al. (2022).

This study examined the effects of time, temperature, and KOH concentration, critical factors influencing biochar characteristics. Each parameter was tested through 20 sample trials, as shown in Table 2. Temperature was identified as a key factor, significantly impacting both yield and adsorption quality. Higher temperatures typically enhance adsorption efficiency by promoting pore development and carbon

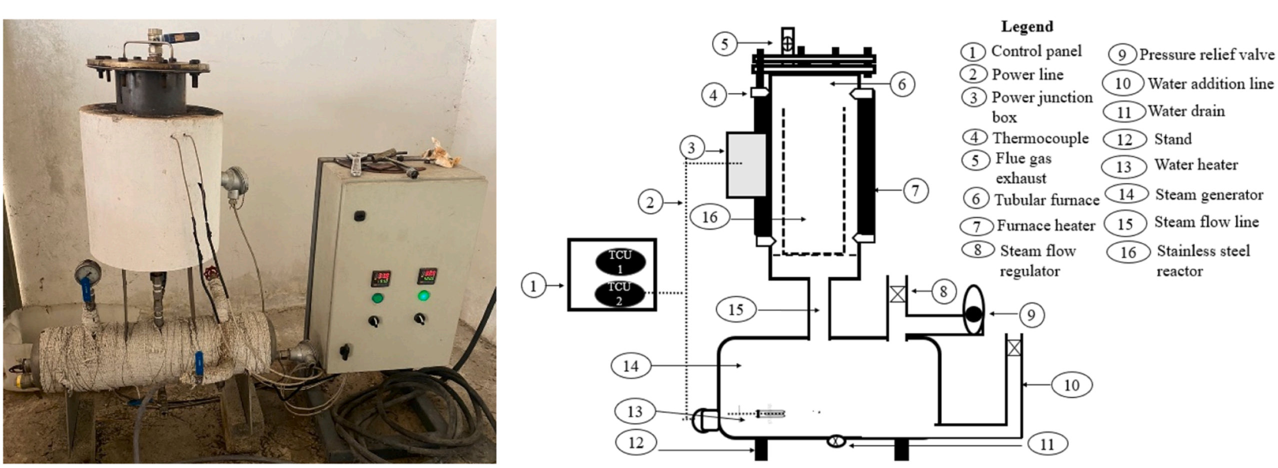

Fig. 2. Schematic illustration depicting the primary components of the pyrolysis system.

Table 2
Optimized experiment design response results.

Run	Factor			Responses		
	Temperature (°C)	Time (min)	KOH (M)	Iodine number (mg/g)	Yield (wt%)	MB adsorption (%)
1	400	90	2	1051.41	22.602	83.291
2	600	90	2	1398.21	18.727	40.747
3	400	200	2	1398.21	25.062	89.831
4	600	200	2	1004.69	19.183	29.752
5	400	90	5	1398.21	26.250	95.221
6	600	90	5	1004.69	16.590	93.593
7	400	200	5	1395.79	19.5	94.83
8	600	200	5	1171.92	16.96	54.11
9	332	145	3.5	1103.07	32.82	96.52
10	668	145	3.5	1395.79	14.30	58.57
11	500	52.5	3.5	1004.69	22.80	93.50
12	500	237	3.5	1398.21	22.03	81.78
13	500	145	0.98	1004.69	18.61	83.47
14	500	145	6.02	1395.79	14.54	65.51
15	500	145	3.5	1395.79	14.23	84.33
16	500	145	3.5	1398.21	19.81	86.96
17	500	145	3.5	1398.21	20.93	86.56
18	500	145	3.5	1004.69	21.61	88.18
19	500	145	3.5	1103.07	20.99	83.08
20	500	145	3.5	1398.21	20.38	83.36

content, as noted by Samsudin et al. (2022), but they can also lead to structural degradation when exceeding optimal limits. Specifically, activation temperatures over 500°C can cause pore collapse, reducing surface area and adsorption capacity.

Activation time also plays a vital role; extended durations help stabilize the biochar structure, further improving adsorption potential. Similarly, KOH concentration affects the degree of chemical impregnation, enhancing surface reactivity and pore volume, both crucial for high adsorption efficiency. Together, these parameters directly influence biochar's pore distribution and surface chemistry, optimizing it for applications in water treatment and soil enhancement.

The biochar that was activated at 332°C for 145 min with a KOH concentration of 3.5 M had the maximum biochar production (32.82 wt %) and the best removal efficiency for MB (96.52 %). Much beyond the SNI Standard's limit of 750 mg/g, the iodine concentrations in the activated carbon varied from 1004.69 to 1398.21 mg/g. The results indicate the efficacy of the proposed biochar production method, which meets industrial standards. The biochar's remarkable adsorption ability is emphasized by its excellent iodine number, rendering it very suitable for various applications, such as gas adsorption and water filtering.

3.2. Interaction effects between factors

A 3D reaction surface plot is shown in Fig. 3(A-C) using a quadratic regression model, illustrating the way the preparation conditions affect the yield, MB adsorption, and iodine number. The plots display the models of linear and quadratic distribution data, with the Y-axis denoting carbonization time and the X-axis indicating carbonization temperature. The response value is shown on the Z-axis, with a consistent concentration of KOH at 3.5 M.

The correlation between carbonization temperature and duration has a modest influence on the production of activated biochar, as seen in Fig. 3 A. Conversely, Fig. 3B demonstrates a significant impact on MB adsorption, indicating that an increase in carbonization temperature leads to growth. This behavior suggests that to fully optimize the pore structure, it is important to further decrease the carbonization temperature. However, continuous carbonization might lead to a decrease in MB adsorption due to increased pore erosion. Extended carbonization duration leads to a notable rise in iodine value at temperatures lower than 500℃, as seen in Fig. 3 C. Nevertheless, the value experiences a sharp decline during the temperature range of 500–600℃. The observed trend reflects the influence of temperature on pore structure stability. At moderate temperatures, the carbonization process efficiently develops micropores, optimizing the surface area for iodine adsorption. However, as the temperature increases beyond 500°C, excessive heat causes micropores to collapse or merge, resulting in larger, less functional pores and reducing the biochar's adsorptive capacity. This phenomenon is consistent with findings from recent studies on the thermal degradation of biochar.

3.3. Data normality

The normal residual plot, shown in Fig. 4, is used to assess the distribution of data with respect to the yield response. This figure evaluates the soundness of the normality assumption in the residuals of the regression model, using the method outlined by Gan et al. (2022), The residuals have a pronounced conformity to a linear red line on the graph, indicating that they adhere to a normal probability distribution. While the dispersion of residual points does not perfectly match the trajectory of the normal line, they roughly adhere to it. Consequently, the yield response data may be described as conforming to a normal distribution, and the actual outcomes closely align with the anticipated values. In addition, according to the research conducted by Nusrat Aman et al. (2023), the normal residual plot demonstrates the normality and uniform distribution of the data when it takes on a linear shape.

3.4. Analysis of variance (ANOVA)

An investigational model with three stages was used in this study. These stages included a sequential model sum of squares, a lack of fit (LOF) test, and model summary statistics. The sum of squares for sequential models is a quantitative measure used to assess the dispersion of data and the appropriateness of a model for regression analysis. The LOF test is used to evaluate the quality of the regression model. Another use of modified R^2 is to measure the impact of study factors on replies.

The ANOVA findings for the factors related to activated biochar synthesis are shown in Table 3, focusing on the iodine number, yield, and MB adsorption. Regarding the yield of activated biochar, the linear model has little explanatory power, as shown by the small sum of squares (0.0019) and the low modified R^2 value of 0.5207. Moreover, the lack of statistical significance in the linear correlation between the suggested factors and yield is shown by the non-significant residual (LOF = 0.3837). This conclusion indicates that the factors included in the model have a minimal effect on the resulting activated biochar.

The corrected R^2 value of 0.4764 and the sum of squares (0.0037) suggest that the linear model used for MB adsorption has a modest ability to explain the observed variability in the data. The updated R^2 value suggests that the model is a better match for the data compared to the yield term (LOF = 0.4122). Nevertheless, the insignificant residual (LOF = 0.4122) suggests that there is no statistically significant linear correlation between the factors being considered and the adsorption of MB.

However, the quadratic model of the iodine number has a noticeable effect, as seen by its high adjusted R^2 value of 0.7361 and somewhat larger sum of squares (0.0012). The quadratic connection between the suggested variables and the iodine number is statistically significant, as shown by the substantial residual (LOF = 0.4365). The findings of this research emphasize that the factors included in the model have a more significant influence on the iodine number compared to the yield and MB adsorption.

Table 4 presents a comprehensive study of the ANOVA findings for yield, MB adsorption, and iodine number in the manufacture of activated biochar. The number of independent data points needed to calculate the sum of squares is referred to as the degrees of freedom (df). The F-value quantifies the factor's statistical significance; higher values indicate a more substantial effect. It quantifies the difference in variance across groups compared to the variation within groups. Typically, a p-

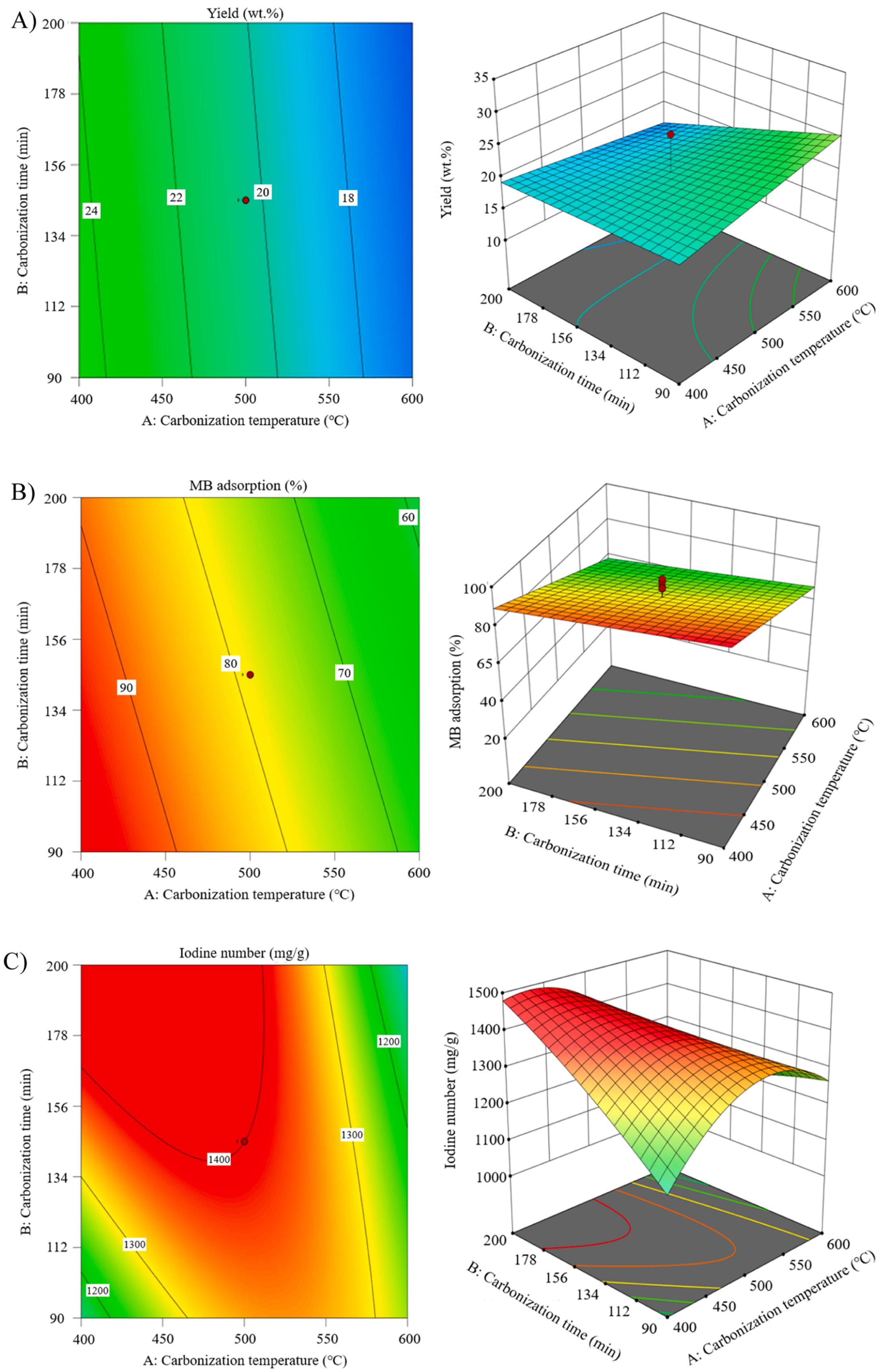

Fig. 3. 3D response surface diagrams of A) activated biochar yield, B) MB adsorption, and C) iodine number.

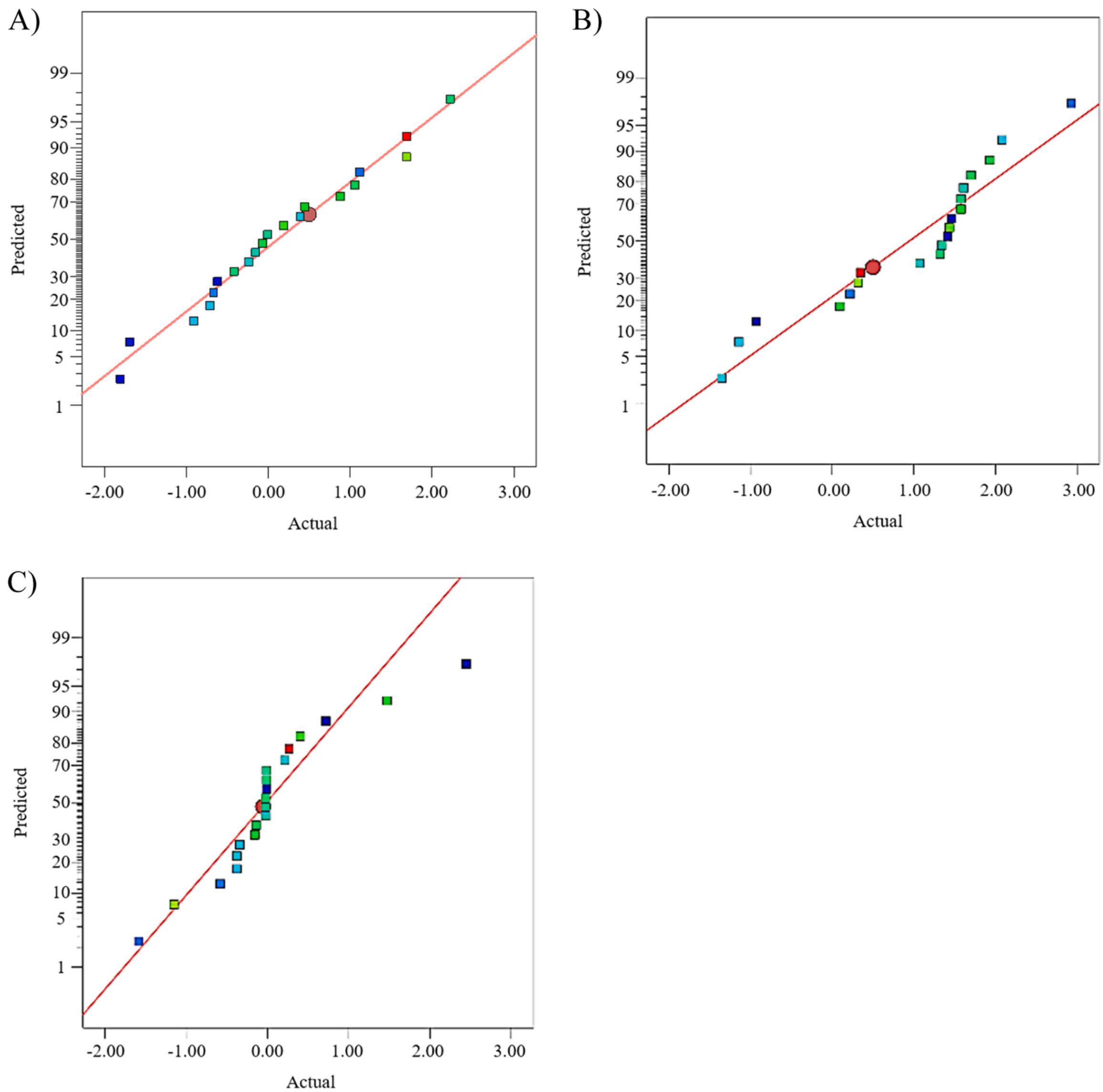

Fig. 4. Predicted against actual of the RSM model for A) activated biochar yield, B) MB adsorption, and C) iodine number.

Table 3
ANOVA for proposed variables in activated biochar production.

Responses	Sum of square	LOF	Adjusted R^2
Yield	0.0019	0.3837	0.5207
MB adsorption	0.0037	0.4122	0.4764
Iodine number	0.0012	0.4365	0.7361

value less than 0.05 is considered statistically significant, as it shows the likelihood of getting the observed F-value randomly.

The yield is significantly affected by the carbonization temperature (F-value: 22.11, p-value: 0.0002). Nevertheless, the p-values for carbonization duration and KOH concentration are not statistically significant at 0.6791 and 0.2619, respectively. This suggests that these factors have little effect on yield determination. The analyzed parameters affect the biochar's adsorption capacity, as reflected by the significant overall model in the MB adsorption model (F-value = 17.08, $p = 0.0037$). The temperature of carbonization is observed to have a strong impact ($p = 0.0008$) on the effectiveness of biochar as an adsorbent for MB, indicating its crucial involvement in the process. In contrast, the impact of carbonization time and KOH concentration on MB adsorption is not statistically significant ($p > 0.05$), suggesting that they have a limited influence in this context.

With a p-value of 0.0029 and an F-value of 6.89, the quadratic model demonstrates that the iodine number is statistically significant. Of particular importance are components AB and A2, namely the carbonization temperature. These factors show F-values of 13.90 ($p = 0.0039$) and 28.02 ($p = 0.0004$, respectively), indicating their strong influence on the iodine number. However, with p-values of 0.4138 and 0.0076, respectively, for the carbonization time parameter B2 and KOH concentration parameter C2, no statistical significance is seen. That these elements interact with one another and have quadratic impacts on biochar's adsorption characteristics is rather noteworthy.

The results show that during the production of activated biochar, many parameters impact MB adsorption, iodine number, and yield in different ways. Although carbonization duration and KOH concentration have less impact on yield and MB adsorption processes, carbonization temperature has a much larger influence. Although the LOF tests, which are not statistically significant, suggest that the models accurately depict the data for yield and iodine number without significant interference from noise, the significant residual in the MB adsorption model ($p < 0.001$) suggests that this discrepancy may be attributed to random fluctuations in the data or the effects of noise.

Table 4
ANOVA of the activated biochar yield, MB adsorption, and iodine number.

Source	Sum of squares	df	Mean square	F-value	p-value	
Iodine number model	5.398×10^5	9	5.998×10^4	6.89	0.0029	significant
A	5.562×10^4	1	5.562×10^4	6.39	0.0300	
B	2.516×10^4	1	2.516×10^4	2.89	0.1199	
C	2.491×10^4	1	2.491×10^4	2.86	0.1216	
AB	1.21×10^5	1	1.21×10^5	13.90	0.0039	
AC	1.164×10^{-10}	1	1.164×10^{-10}	134×10^{-14}	1.0000	
BC	1.164×10^{-10}	1	1.164×10^{-10}	134×10^{-14}	1.0000	
A^2	2.439×10^5	1	2.439×10^5	28.02	0.0004	
B^2	6.33×10^3	1	6.33×10^3	0.7272	0.4138	
C^2	9.652×10^4	1	9.652×10^4	11.09	0.0076	
Residual	8.705×10^4	10	8.705×10^3			
LOF	8.705×10^4	5	1.741×10^4	9.906×10^3	0.1000	not significant
Pure error	8.79	5	1.79			
Cor total	6.268×10^5	19				
Yield model	220.81	3	73.60	7.88	0.0019	significant
A	206.52	1	206.52	22.11	0.0002	
B	1.66	1	1.66	0.1775	0.6791	
C	12.63	1	12.63	1.35	0.2619	
Residual	149.43	16	9.34			
LOF	112.24	11	10.20	1.37	0.3837	not significant
Pure error	37.19	5	7.44			
Cor total	370.23	19				
MB adsorption model	3791.01	3	1263.67	6.76	0.0037	significant
A	3191.66	1	3191.66	17.08	0.0008	
B	300.21	1	300.21	1.61	0.2231	
C	299.14	1	299.14	1.60	0.2239	
Residual	2989.81	16	186.86			
LOF	2967.64	11	269.79	60.83	0.0001	significant
Pure error	22.18	5	4.44			
Cor total	6780.82	19				

3.5. Optimization analysis

An analysis of experimental results demonstrates that the carbonization temperature, duration, and concentration of KOH have a combined impact on the generation of activated biochar. The optimization analysis of the Design-Export program allows for the discovery of elements that meet goals or show optimum synergy. Consequently, it was used to assess the highest amount of char produced, the highest iodine quantity, and the adsorption of MB. The program uses the word "desirability" to indicate advantageous circumstances for product yield and attributes; a number nearing 1 indicates the presence of such conditions. Subsequently, validation tests were conducted according to the software's parameters, and the results were compared to the projected outcomes.

According to the data shown in Table 5, the three elements are essential for ensuring that production conditions remain within the desired limits. Factor A has precedence in importance, followed by components B and C. Emphasizing the importance of prioritizing iodine quantity and MB adsorption is crucial since yield and MB adsorption are tightly correlated. To provide the most favorable manufacturing circumstances, the designated parameters for factors A, B, and C are as follows: The temperature ranges from 400 to 600°C, the duration ranges from 90 to 200 min, and the concentration ranges from 2 to 5 M. The achieved values for iodine number, yield, and MB adsorption are shown by their actual measurements, which aid in assessing the process under specific circumstances.

Table 5
Optimization parameters for iodine number, yield, and MB adsorption.

Factors	Goals	Importance	Low	High
A	In range	+++	400	600
B	In range	+++	90	200
C	In range	+++	2	5
Iodine number	Maximize	+++++	1004.69	1398.21
Yield	Maximize	+++	14.23	32.82
MB adsorption	Maximize	+++++	29.75	96.51

The contour plots shown in Fig. 5 were generated using RSM to predict the best responses within the defined range of factors. The outcomes with the greatest attainable level are shown in red, followed by orange, yellow, and subsequently green and blue. The expected values for iodine number, yield, and MB adsorption are concisely shown in Table 6. The results are as follows: 1398.21 mg/g, 23.78 wt%, and 93.95 %, respectively. Given the specified circumstances, the resulting level of desirability was 0.845.

To confirm the optimal predicted point of the RSM, the ratio between the expected and actual responses was calculated (Nusrat Aman et al., 2023). To achieve this goal, the pyrolysis process was modified by adjusting the activator concentration, carbonization duration, and temperature to the projected ideal values of 4.068 M, 165.84 min, and 400°C, respectively. The iodine number was measured to be 1395.73 mg/g, the yield was found to be 25.67 wt%, and the MB adsorption was determined to be 95.249 % during later verification tests. Negligible disparities were noted between the projected and confirmed values. The observed differences between the anticipated and verified values specifically relate to the iodine number response (2.482 mg/g), yield (1.879 wt%), and MB adsorption (0.407 %).

3.6. Comparison with prior research and commercial biochar

Table 7 compares the performance metrics of the biochar produced in this study with those reported in prior research. The optimized biochar achieves a high iodine number and methylene blue adsorption capacity, indicating superior adsorption efficiency suitable for environmental applications. The biochar derived from coconut waste demonstrates significant advantages over previous research due to optimized pyrolysis and activation conditions. Pyrolysis at 400°C for 165.84 min, combined with activation using 4.068 M KOH at 70°C for 72 h, resulted in a biochar yield of 25.67 %, an iodine number of 1395.7 mg/g, and MB adsorption capacity of 129.2 mg/g. These results reflect not only enhanced pore structure and surface area, which are essential for effective adsorption, enabling practical applications in soil enhancement and wastewater treatment. This optimized approach supports sustainable waste management by transforming coconut waste into valuable biochar for environmental remediation purposes.

In contrast, higher pyrolysis temperatures used in studies by da Silva et al. (2024) and Akila et al. (2018) led to significantly lower adsorption capacities (33.1 mg/g and 65.5 mg/g, respectively), due to excessive carbonization and pore collapse. This underlines the advantage of maintaining a moderate pyrolysis temperature of 400°C. Differences in activation methods and temperature control have enhanced pore formation and surface functionalization in this study's biochar. Consequently, this study's biochar outperforms previous studies, where its iodine number is 43.4 % higher than Darmawan et al. (2022), 153 % higher than Akila et al. (2018), and nearly identical to commercial biochar, differing by only 0.2 %. Additionally, its MB adsorption capacity shows a 6.5 % improvement over Darmawan et al. (2022), a

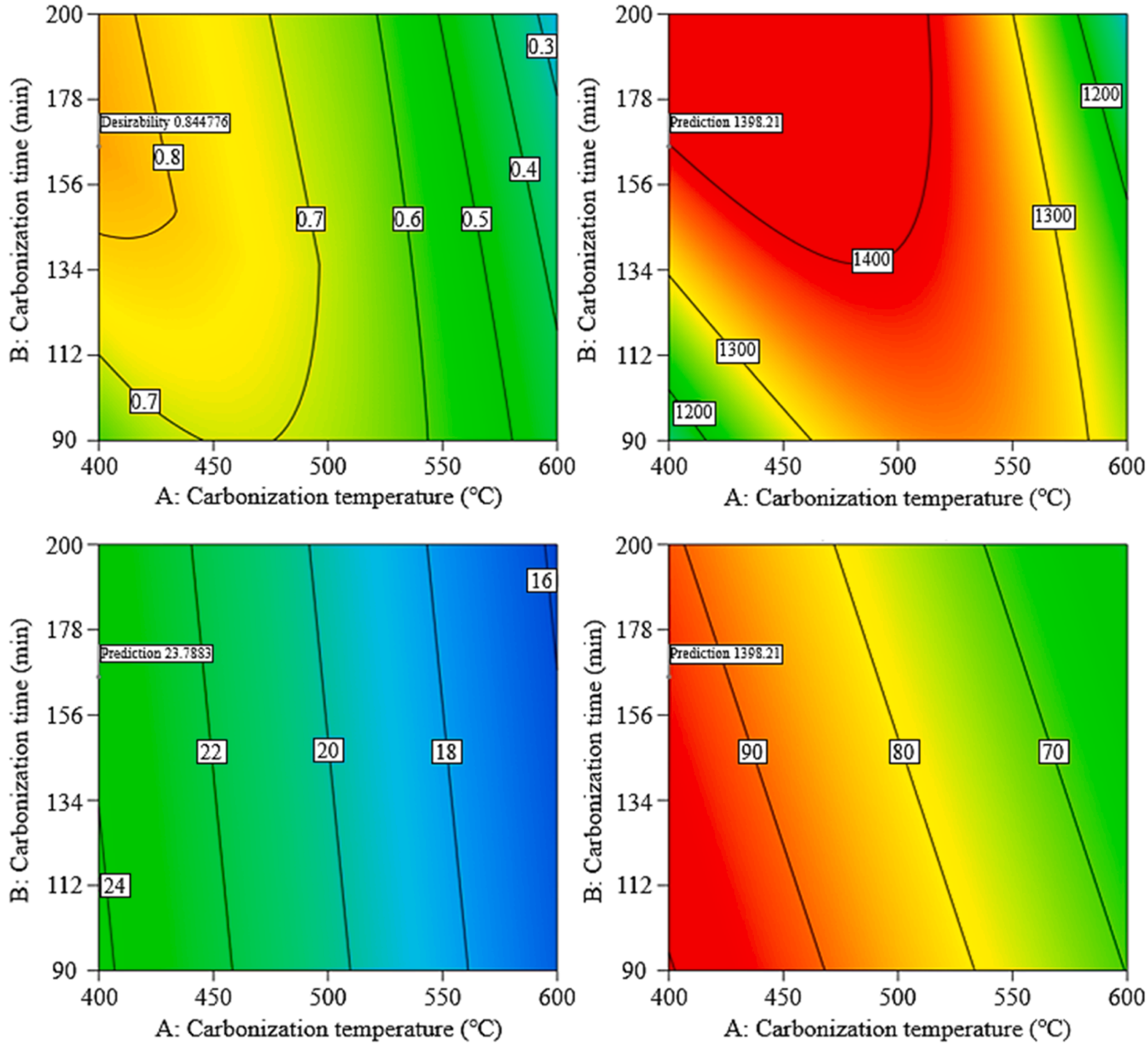

Fig. 5. Contour plots of the predicted models.

Table 6
The predicted optimum carbonization parameters and outcomes.

Carbonization temperature	Carbonization time	KOH concentration	Iodine number	Yield	MB adsorption	Desirability
400.0	165.84	4.068	1398.21	23.79	93.94	0.845

significant 290.6 % improvement over da Silva et al. (2024), a 97.1 % improvement over Akila et al. (2018), and a 6.3 % improvement over commercial biochar.

Given the method's efficiency and yield, the optimized biochar production process holds promising scalability potential. By applying this method at an industrial level, it is possible to repurpose significant quantities of agricultural waste, contributing to both environmental and economic sustainability. Such scalable waste-to-resource processes offer a viable solution for reducing landfill burden while generating high-performance materials for environmental applications.

4. Conclusion

This study effectively addresses organic waste by converting young coconut husks into high-quality biochar, optimized using Response Surface Methodology (RSM). The identified optimal conditions, i.e. 400°C, 165.8 min, and 4.07 M KOH, yielded biochar with an iodine number of 1398.2 mg/g, an MB adsorption efficiency of 93.9 %, a yield of 25.7 wt%, and a 90.2 % attractiveness index, exceeding the 84.5 % of conventional methods. 3D-response plots revealed that while carbonization temperature and duration minimally affect biochar yield, lower temperatures improve MB adsorption and iodine number by enhancing pore structure. Higher temperatures, in contrast, erode pores and reduce adsorption. Model accuracy was verified by residual plots, and ANOVA showed a significant effect of temperature on adsorption properties ($p < 0.05$), with time and KOH concentration having lesser effects ($p > 0.05$). This biochar achieved an iodine number 43.4–153 % higher than prior studies and a 6.5–290.6 % improvement in MB adsorption, nearly matching commercial biochar, underscoring the potential of this method for sustainable waste management applications.

CRediT authorship contribution statement

Akhmad Adi Sulianto: Validation, Supervision, Methodology, Conceptualization. **Talitha Philofia Sopandi:** Writing – review & editing, Writing – original draft, Visualization, Methodology,

Table 7
Comparison of the biochar derived from coconut waste in this study with previous research and commercial products.

Pyrolysis conditions	Activation conditions	Yield (%)	Iodine number (mg/g)	MB adsorption (mg/g)	References
400 °C, 165.84 min	4.068 M KOH, 70 °C, 72 h	25.67	1395.7	129.2	This study
400 °C, 4 h	Steam (H_2O), 10 h		973.9	121.3	(Darmawan et al., 2022)
700 °C, 90 min	-	23.3	-	33.1	(da Silva et al., 2024)
400–500 °C	-	-	-	36.5	(Prasoetsoph et al., 2023)
200 °C, 84 min	-	-	-	28.6	(Danso-Boateng et al., 2023)
800 °C, 60 min	-	25.6	550	65.5	(Akila et al., 2018)
-	-	-	1398.2	137.4	Commercial biochar

Investigation, Formal analysis, Data curation. **Mohammed Abdillah Ahmad Farid:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **Mohd Shamzi Mohamed:** Validation, Supervision, Methodology, Conceptualization. **Mohd Zulkhairi Mohd yusoff:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Fajri Anugroho:** Validation, Supervision, Methodology, Conceptualization. **Hendrix Yulis Setyawan:** Validation, Supervision, Methodology, Conceptualization.

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.

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Data availability

No data was used for the research described in the article.

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