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Adsorption of Rhodamine B by Coconut Shell Activated Carbon

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ABSTRACT: Pollution caused by dye waste from the textile industry, particularly Rhodamine B, threatens human health and, if released into aquatic environments on a large scale, can negatively impact aquatic ecosystems. Environmental pollution caused by this dye can be prevented through adsorption using activated carbon. This study aims to evaluate the efficiency of Rhodamine B dye removal from synthetic wastewater by varying the mass of activated carbon from coconut shell carbon and to determine the appropriate adsorption isotherm model. The experiment was conducted by activating coconut shell carbon physically using a furnace at a temperature of 700°C for 2 hours and chemically using 2.5 M KOH and soaked for 20 hours with a ratio of 1: 3 (m/v). From the results of the BET analysis, the surface area of coconut shell activated carbon is 1212.02 m^2/g. The results based on variations in adsorbent mass showed the best mass of 3 g with the smallest final concentration of 2.72 ppm, an equilibrium time of 120 minutes, and an adsorption effectiveness of 86.13%. The appropriate adsorption isotherm model is the Langmuir isotherm. These results indicate that coconut shell activated carbon has the potential to reduce Rhodamine B levels in textile industry liquid waste.

Keywords: adsorption; adsorbent; coconut shell activated carbon; rhodamine B; adsorption isotherm

1. Introduction

Environmental pollution caused by dye waste continues to increase. Waste generated from the textile industry often contains non-biodegradable organic compounds which can cause environmental pollution, particularly water pollution (Nguyen et al., 2021). It is estimated that textile industry wastewater typically contains 10% to 25% of the dyes used during the dyeing process (Y. Liu et al., 2024). This waste is toxic because it contains heavy metals, dyes, and several hazardous compounds. Most of these heavy metals are water degradable persistent in water, highly toxic, and carcinogenic (Dutta, 2022).

In the textile industry, Rhodamine B is a basic dye that is important in the fabric dyeing process (Rafique et al., 2020). According to Sari (2024), Rhodamine B is a dye that appears as a green or reddish-purple crystalline powder, odorless and highly soluble, producing a bright red fluorescent solution commonly used for coloring textiles, paints, paper, and fabrics. The chlorine present in Rhodamine B is highly reactive and toxic. Accumulation of Rhodamine B in the liver can lead to impaired liver function, manifesting as liver cancer and tumor development (Harahap et al., 2024).

Environmental pollution caused by dye wastewater can be handled chemically through the use of coagulants and physically through adsorption using activated carbon (Wante et al., 2024). Several methods have been employed for dye removal, including reverse osmosis and ion exchange, both of which are expensive and complex methods. Consequently, research is needed on low-cost methods, one of which is adsorption (Siswanti et al., 2024). Essentially, adsorption involves a mass transfer process in which a substance is transferred from a liquid phase to a solid surface. For the adsorption of carcinogenic dyes from textile industrial wastewater using activated carbon as an adsorbent, the mass transfer of the dye to the surface of the activated carbon occurs, thereby reducing the concentration of carcinogenic dyes in the wastewater as the dyes move to the surface of the adsorbent.

The process of making activated carbon begins with the production of charcoal through a carbonization process. Materials that can be used as raw materials for charcoal are materials that contain high cellulose, for example agricultural and plantation biomass waste such as tree branches, peanut shells, dry leaves, corn cobs, rice husks, straw, and coconut shells (Nonsawang et al., 2024). If the carbonized charcoal is to be used as an adsorbent to absorb dye waste, especially Rhodamine B, an activation process is

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required to increase the surface area of the pores that will come into contact with the dye. The activation process can be carried out physically by heating using a furnace at a high temperature. However, if activation is only carried out by a physical process, the quality of the activated carbon is less than satisfactory, so it needs to be activated chemically, one of which is by soaking it in a KOH solution for a certain time.

Activation aims to enlarge the pore structure by breaking hydrocarbon bonds or oxidizing surface molecules. This process changes the physical characteristics of the charcoal, resulting in an increased surface area, which subsequently enhances its adsorption capacity (Wante et al., 2024). Activation consists of two stages: physical and chemical activation. Physical activation of coconut shell charcoal can be carried out at temperatures 600-800°C, Meanwhile, chemical activation can be carried out using KOH, H_3PO_4, NaOH, and H_2SO_4 (Liang et al., 2020; Mercileen et al., 2023; Yu et al., 2024).

Although activation using KOH has been widely applied, the optimum adsorbent dosage of coconut shell-based activated carbon for Rhodamine B adsorption process has not been widely studied, and the most dominant adsorption isotherm model in this system has not been determined definitively. Therefore, this study was conducted to evaluate the efficiency of Rhodamine B dye adsorption from synthetic wastewater through variations in activated carbon dosage and to determine the most suitable adsorption isotherm model based on the adsorption capacity of Rhodamine B on the adsorbent.

2. Materials and Methods

2.1. Materials

The main raw material used in this study is coconut shell carbon obtained from a producer located at Mrisi RT 10/28 No. 41, Bantul Regency, Special Region of Yogyakarta. Rhodamin B obtained from Wenter Wahono Shop, Jalan Gajah Suranto No. 2, Baluwarti, Pasar Kliwon District, Surakarta City, and supporting materials used are 95% KOH and 33% HCl, were obtained from CV Progo Mulyo, located at Caturtunggal, Sleman, Yogyakarta.

2.2. Equipment

The equipment used are an electrical stirrer (Twister Digital Overhead, Input: DC24V 5A) and UV-Vis Spectrophotometer (Spectral bandwidth: 1.8 nm, Light source: Xenon flash lamp, Detectors: Dual silicon photodiodes, Wavelength range: 190 – 1100 nm, Wavelength accuracy: 1.0 nm).

2.3. Methods

2.3.1 Preparation of Coconut Shell Activated Carbon

The reduced size coconut shell carbon is then sieved using a -18 + 20 mesh sieve. Next, the coconut shell carbon is activated physically and chemically. Physical activation use a furnace at a temperature of 700 ± 5ºC for 2 hours, while chemical activation use 2.5 M KOH for 20 hours with a ratio of 1:3 (m/v). After chemical activation, the coconut shell carbon is dripped with 1-2 drops of dilute 1 M HCl solution, then washed using aquadest until the pH is neutral and dried in an oven at a temperature of 110°C until a constant mass. The dried coconut shell activated carbon was analyzed for BET surface area using a Nova surface area analyzer (Quantachrome Nova 1200e instrument)

2.3.2 Determination of the Standard Curve

The determination of the standard calibration curve began by identifying the maximum adsorption wavelength of Rhodamine B solution using a UV-Vis spectrophotometer within the wavelength range of 500–600 nm (Utami & Purnamawati, 2014). The results of the wavelength at the maximum adsorption will be used to create a standard curve by making a 20 ppm Rhodamine B solution and then measuring its absorbance using a UV-Vis spectrophotometer. This experiment was repeated to determine the absorbance value of the Rhodamine B solution diluted twice

2.3.3. Rhodamine B Adsorption with Variation in Adsorbent Mass

The adsorption process was carried out by adding 0.5 g of coconut shell charcoal into 100 mL of Rhodamine B solution with a concentration of 20 ppm, then stirred at a speed of 200 ± 2 rpm at room temperature. The concentration of the liquid phase was measured every 10 minutes, and each measurement was repeated twice (n = 2). The experiment was continued until equilibrium conditions were reached, then repeated with variations in the mass of coconut shell charcoal of 1.0; 1.5; 2.0; 2.5; and 3.0 g.

2.3.4. Determination Effectiveness Adsorption

The adsorption effectiveness of Rhodamine B was determined by measuring the ratio between the mass of Rhodamine B adsorbed on the adsorbent and the initial mass of Rhodamine B present in the solution.

The effectiveness at any given time (E_t) was determined using the following equation (1):

$$E_t = \frac{C_0 - C_t}{C_0} \times 100\% \quad (1)$$

The adsorption effectiveness at equilibrium (Ee) was calculated using the following equation (2):

$$E_e = \frac{C_0 - C_e}{C_0} \times 100\% \quad (2)$$

2.3.5. Equation Model Isotherm Adsorption

The mathematical equation used to determine the adsorption capacity at equilibrium conditions (Q_e) is:

$$Q_e = \frac{C_0 - C_e}{m} \times V \quad (3)$$

Equation model equilibrium isotherm adsorption used namely Langmuir, Freundlich, Halsey, Jovanovic, and Flory (Bayu et al., 2023):

1) Isotherm Langmuir

$$\frac{1}{Q_e} = \frac{1}{K_L Q_{maks}} \frac{1}{C_e} + \frac{1}{Q_{maks}} \quad (4)$$

$$R_L = \frac{1}{1+K_L C_e} \quad (5)$$

2) Isotherm Freundlich

$$\log(Q_e) = \log(K_f) + \frac{1}{n}\log(C_e) \quad (6)$$

3) Isotherm Halsey

$$Q_e = \frac{1}{nH}\ln(K_H) - \frac{1}{nH}\ln(C_e) \quad (7)$$

4) Isotherm Jovanovic

$$\ln(Q_e) = \ln(Q_{maks}) - KjC_e \quad (8)$$

5) Isotherm Flory-Huggins

$$\log\left(\frac{\theta}{C_e}\right) = \log(K_{FH}) + n\log(1-\theta) \quad (9)$$

3. Results and Discussion

3.1. BET Surface Area

BET surface area analysis aims to identify the surface properties of porous materials, such as surface area, pore size, and pore volume (Duan et al., 2019). In previous research, the characterization results of coconut shell activated carbon to adsorb Rhodamine B activated with H_3PO_4, produced a surface area of 408.59 m²/g (Yu et al., 2024). As a comparison, Yang & Han (2018) reported that lysine adsorption on coconut shell activated with KOH produced a BET surface area of 1118.2 m²/g. In this study, the BET surface area was measured at 1212.02 m²/g. This indicates that coconut shell charcoal activated physically at 700 °C for 2 hours and chemically with 2.5 M KOH has a larger surface area, allowing more adsorbate molecules to be adsorbed on the adsorbent surface.

3.2. Influence Mass Adsorbent on Concentration

The effect of variations in adsorbent mass on the concentration of Rhodamine B in the liquid phase at various times is shown in Figure 1. When an adsorbent mass of 0.5 g is added, the longer the contact time, the lower the dye concentration in the liquid phase, indicating that more dye molecules are adsorbed onto the adsorbent surface over time. However, as the contact time continues to increase, the change in concentration becomes progressively smaller, eventually reaching equilibrium. This phenomenon occurs because, at the initial stage of contact, a large number of active sites on the adsorbent surface are still available, allowing for a faster mass transfer of dye molecules from the liquid phase to the adsorbent. However, as the contact time increases, the availability of active surface area gradually decreases, resulting in a slower mass transfer rate. Consequently, the change in concentration over time becomes smaller until equilibrium concentration is reached. (Siswanti et al., 2024). This behavior also applies to other adsorbent masses. As the amount of adsorbent increases, the time required to reach equilibrium becomes shorter.

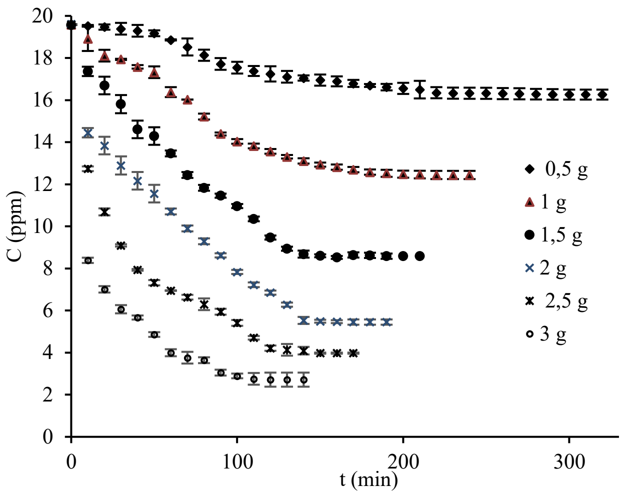


Figure 1. The effect of variations in adsorbent mass on concentration at times t. Average values are shown (n =2). Standard deviations are shown in vertical lines

As shown in Figure 2, a greater adsorbent mass leads to a faster attainment of equilibrium

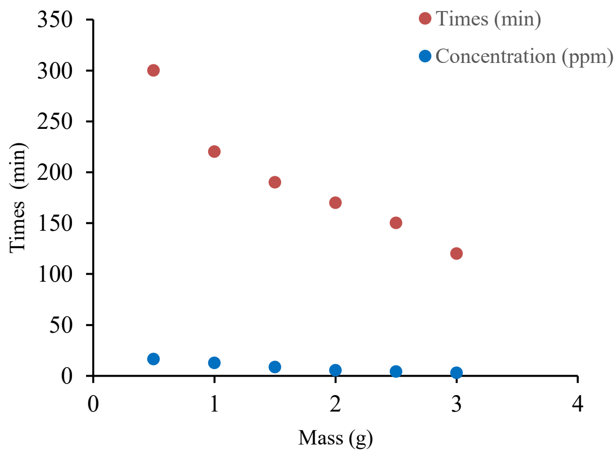


Figure 2. The effect of mass adsorbent on time and concentration equilibrium

3.3. Effectiveness Adsorption

The adsorption capacity of coconut shell activated carbon against Rhodamine B at various adsorbent masses between 0.5 to 3 g with observation time intervals every 10 minutes until equilibrium conditions are reached is shown in Figure 3. At an adsorbent mass of 0.5 g, the adsorption effectiveness increases with increasing contact time until equilibrium is reached. This indicates that the length of contact time or stirring plays an important role in reducing the dye concentration in the liquid phase, because it allows for more intense interactions between Rhodamine B molecules and the adsorbent surface, thereby increasing the adsorption effectiveness (Syakir et al., 2023). A similar pattern is also seen in other adsorbent mass variations.

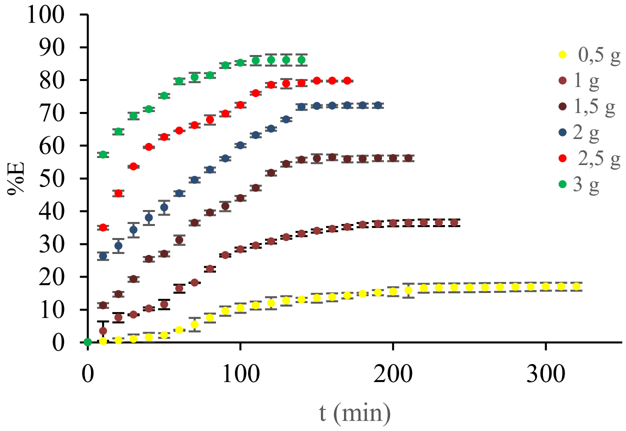


Figure 3. The correlation between time and effectiveness adsorption. Average values are shown (n=2). Standard deviations are shown in vertical lines

When using an adsorbent mass of 3 g, the adsorption effectiveness in the first 10 minutes reached 57.19%, this indicates that increasing the amount of adsorbent significantly increases the effectiveness of the adsorption process. In comparison, at an adsorbent mass of 0.5 g, the adsorption effectiveness at the same time was only 0.30%. The highest adsorption efficiency value was obtained at 86.13% after a contact time of 120 minutes with an adsorbent mass of 3 g. The effect of variations in adsorbent mass on adsorption efficiency at equilibrium conditions is shown in Figure 4.

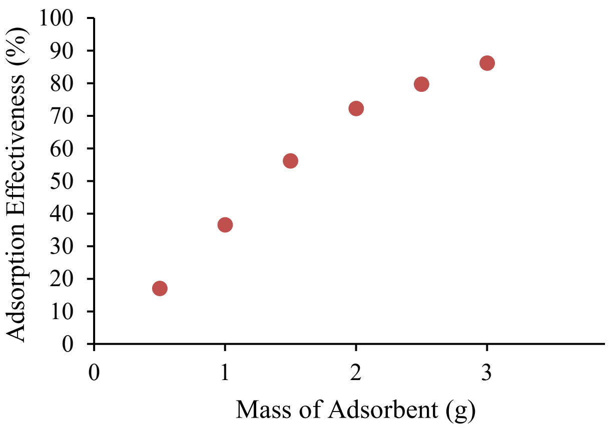
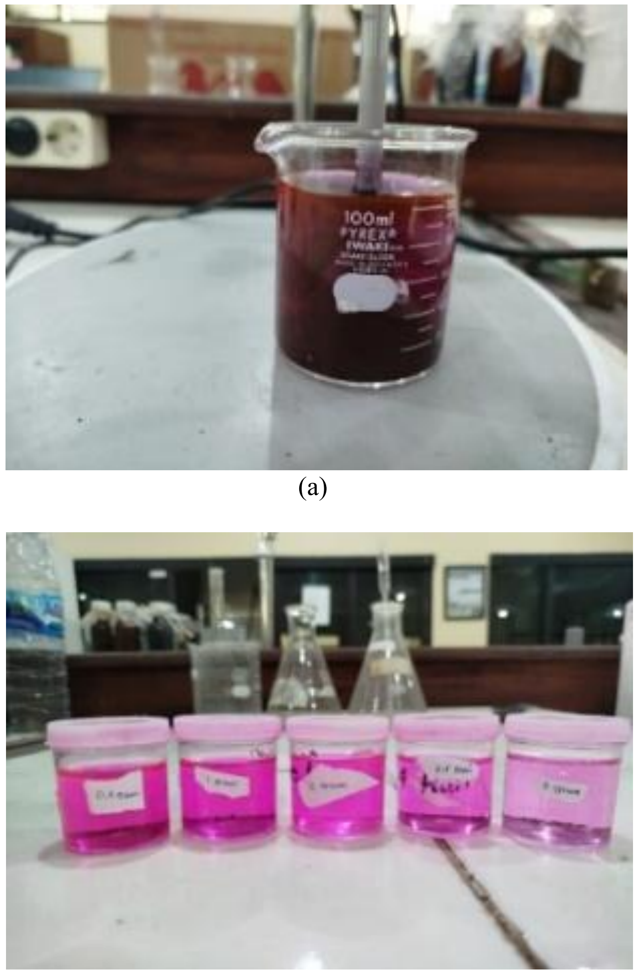


Figure 4. Graph connection between Adsorbent Mass and Effectiveness Adsorption at the time Equilibrium

The influence of adsorbent mass on adsorption efficiency can be visually observed through the color difference between Rhodamine B solution before and after the adsorption process. An increase in the amount of adsorbent tends to result in a clearer synthetic Rhodamine B waste solution. As shown in Figure 5, the use of 3 g of adsorbent yields the highest clarity compared to other adsorbent masses. These findings further support the conclusion that increasing the mass of the adsorbent contributes to an improvement in the overall quality of the adsorption process



(a)

(b)

Figure 5. (a) Rhodamine B synthetic waste before adsorption, (b) Rhodamine B synthetic waste after adsorption with various mass variations

3.4. Modelling Isotherm Adsorption

The adsorption isotherm model characterizes the relationship between the equilibrium concentration of the adsorbate in the liquid phase and the quantity of adsorbate adsorbed onto the solid phase at a constant temperature. This model is essential for comprehending the adsorption behavior of Rhodamine B and for developing effective adsorption systems (Wang & Guo, 2020). In this study, five isotherm models were evaluated using equilibrium data obtained from experiments conducted with varying adsorbent masses of 0.5 g, 1.0 g, 1.5 g, 2.0 g, 2.5 g, and 3.0 g.

The Langmuir isotherm model postulates that adsorption equilibrium is established when the rates of adsorption and desorption are equal (Ye et al., 2021). It assumes monolayer adsorption on the adsorbent surface, where all adsorption sites have uniform capacity. Furthermore, the model treats the adsorbed species as ideal,

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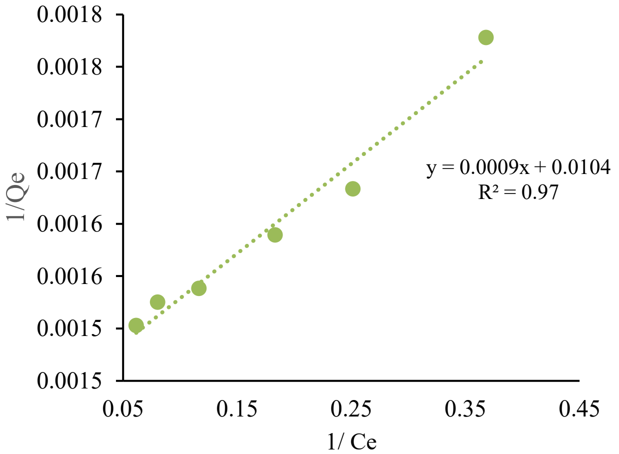

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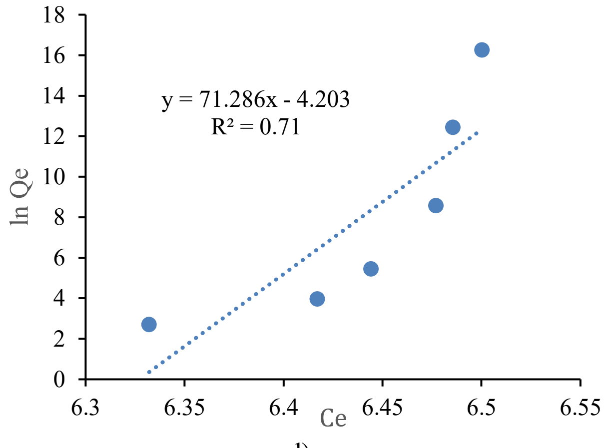

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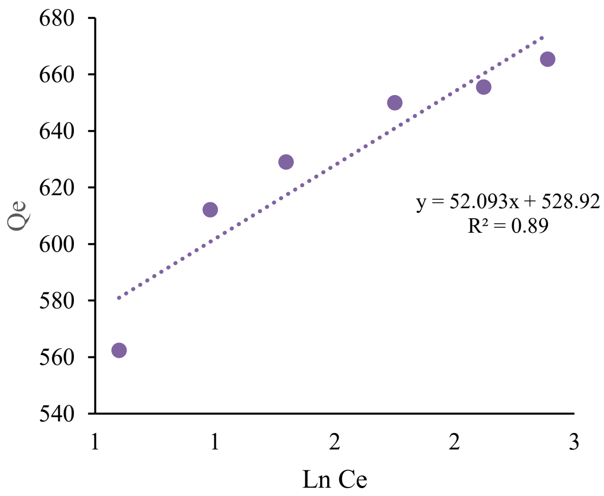
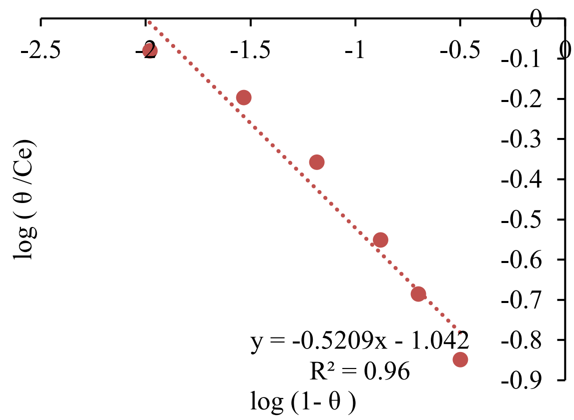
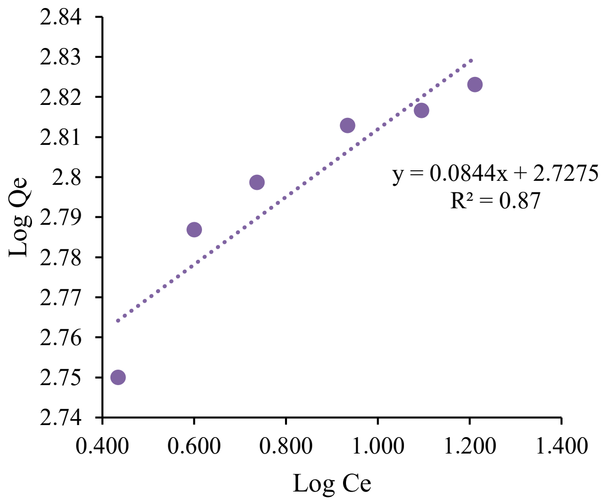


(b)



e)



c)

Figure 6. Isotherm curves : (a). Langmuir, (b). Freundlich, (c). Halsey, (d). Jovanovic,(e). Flory-Huggins

indicating no interactions between adsorbate molecules or between adsorbate and adsorbent. The adsorption affinity and effectiveness of the adsorbent can be evaluated using the separation factor or equilibrium parameter (R_L) (Singh & Bhateria, 2020). The relationship between concentration and adsorption capacity at equilibrium, modeled using the Langmuir isotherm, is presented in Figure 6. (a). The calculated separation factor (R_L) value of 0.1913 indicates that the adsorption process in this study is advantageous, with negligible occurrence of desorption (Bayu et al., 2023) The Freundlich isotherm is an empirical model used to describe physical adsorption.

It assumes the adsorbent surface is heterogeneous with varying adsorption energies, enabling multilayer adsorption. This model defines adsorption on heterogeneous surfaces using the parameters n, which reflects the degree of non-linearity, and 1/n, which indicates the adsorption intensity or strength (Brazesh et al., 2021). The relationship between concentration and adsorption capacity at equilibrium, modeled using the Freundlich isotherm, is presented in Figure 6. (b). The calculated value of n=11.8483 indicates that n>1 and 0<1/n<1, suggesting that the adsorption process in this study proceeds via physisorption and occurs on a heterogeneous surface (Bayu et al., 2023).

The Halsey isotherm model is utilized to describe multilayer adsorption occurring over a relatively wide distance from the adsorbent surface (Bayu et al., 2023). The relationship between concentration and adsorption capacity at equilibrium, modeled using the Halsey isotherm, is illustrated in Figure 6c.

The Jovanovic isotherm is a modification of the Langmuir isotherm that accounts for the possibility of adsorbed molecules detaching from the adsorbent surface (Chu et al., 2023). The relationship between concentration and adsorption capacity at equilibrium, modeled using the Jovanovic isotherm, is presented in Figure 6d. Isotherm Flory- Huggins assumes that the adsorption process occurs spontaneously (Pourhakkak et al., 2021). The relationship between θ/Ce with (1- θ) shown in Figure 6e.

Table 1. Results isotherm adsorption models and its parameters

Isotherm Model	Parameter	Value
Langmuir	Q_{max} (mg/g)	96.15
	K_L (L/mg)	1.55
	R_L	0.19
	R^2	0.97
Freundlich	K_F	15.29
	n	11.84
	R^2	0.87
Halsey	K_H	74.41
	n_H	0.08
	R^2	0.88
Javanovic	Q_{max} (mg/g)	66,89
	K_j (L/mg)	71.28
	R^2	0.70
Flory-Huggins	K_{FH}	1.04
	n_{FH}	-0.52
	R^2	0.96

The results of the adsorption isotherm model fitting are summarized in Table 1, which compares the data from each isotherm model. The Langmuir isotherm model proved to be the most appropriate to describe the adsorption of Rhodamine B, as it showed the highest coefficient of determination (R^2), which was 0.97, among all the models tested. This finding indicates that the adsorption process occurs at specific homogeneous sites on the adsorbent surface. In addition, the adsorption of Rhodamine B only forms a monolayer, where each adsorbed molecule occupies a specific site on the adsorbent surface, and each site only binds one molecule or atom. The Langmuir constant (K_L) was calculated at 1.56 L/mg, with a separation factor (R_L) value of 0.19, indicating that the adsorption process is favorable because it can be controlled under certain conditions and adsorption occurs normally (Nandiyanto et al., 2020). The maximum adsorption capacity (Qmax) determined at room temperature conditions was 96.15 mg/g. This maximum adsorption capacity is significantly higher than that reported in previous studies using 2 M KOH as an activator, which showed a Qmax of 90.90 mg/g according to the Langmuir model (Mercileen et al., 2023). This value is also higher than the adsorption capacity reported for Crystal Violet using H_3PO_4 as an activator, which showed a maximum adsorption capacity (Q_{max}) of 26.31 mg/g (Yu et al., 2024). Coconut shell charcoal activated with KOH has a higher adsorption effectiveness compared to other activators, mainly due to the unique chemical activation mechanism of KOH, which creates a highly porous structure and increases the surface area of the activated carbon (P. Liu et al., 2024). KOH activation causes physical and chemical changes in the material, such as pore expansion, micropore widening, and removal of volatile components. This increases the accessibility of adsorbate molecules to the adsorption sites (Mercileen et al., 2023). In this study, increasing the concentration of KOH can increase the surface area of the adsorbent pores, thereby increasing the effectiveness of dye absorption.

3.5. Comparison to previous studies

Table 2 shows that several studies have observed the potential use of activated carbon as an adsorbent to remove dyes, one of which is Rhodamine B, from textile industrial wastewater. Although existing research is still limited to the adsorption of Rhodamine B at relatively low concentrations, namely 5 and 10 ppm (Yustinah et al., 2022; Syakir et al., 2023; Walidah et al., 2022; Yu et al., 2024; Saputra et al., 2025). However, it should be noted that the concentration of Rhodamine B in aquatic environments affected by textile wastewater is usually higher, ranging from 150 to 3000 ppm (Nguyen et al., 2021). To address this gap, research is needed to increase the initial concentration of Rhodamine B, as an effort to approach the actual conditions of wastewater.

Table 2 also shows that the use of adsorbent from coconut shell activated charcoal for Rhodamine B adsorption is still limited, namely it is used as an adsorbent for Rhodamine B adsorption with low concentrations (Yu et al, 2024) and used as an adsorbent for crystal violet adsorption with a concentration of 80 ppm (Mercileen et al, 2022). The abundant availability of coconut shell resources in Indonesia can be utilized as a raw material for coconut shell charcoal production, with production reaching around 66,200 tons per year (Arena et al., 2016; Lutfi et al., 2021). This potential can be used as a basis for considering choosing coconut shell charcoal as an adsorbent to remove Rhodamine B in liquid waste. Based on this description, as an effort to increase the effectiveness of adsorption against Rhodamine B, this study develops previous research. The development effort from previous research is that the concentration of Rhodamine B is increased to 20 ppm, the adsorbent used is activated charcoal from coconut shell which is physically activated at 700°C and chemically activated by soaking in a 2.5 M KOH solution for 20 hours. The concentration of this KOH solution is higher than the 2 M KOH concentration used in crystal violet adsorption and achieves an adsorption efficiency of 88.58% (Mercileen et al., 2023).

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Table 2. Comparison to previous result on Rhodamin B and coconut shells

Adsorbent	Activation (Physics; Chemical)	Adsorbate	BET Surface Area (m^2/g)	%E	Refferences
Ketapang leaves	0,3 M H_2SO_4	Rhodamine B 10 ppm	-	91.86	(Walidah & Takwanto, 2022)
Coconut shell activated carbon	600ºC for 2 h ;2 M H_3PO_4	Rhodamine B 10 ppm	408.59	95.84	(Yu et al., 2024)
Graphene Oxide	-	Rhodamine B 5 ppm	-	79.00	(Syakir, et al., 2023)
Activated carbon coffee grounds	400ºC for 20 min; 0,1 N H_3PO_4 for 48 h	Rhodamine B 5 ppm	-	92.20	(Yastinah et al., 2022)
Coconut shell activated carbon	700ºC for 2 for; 2 M KOH for 20h	Crystal Violet 80 ppm	-	88.58	(Mercileen et al., 2023)
Graphene Oxide-Bacterial Celluolose composites	Sonication for 30 min	Rhodamine B 10 ppm	-	99.50	(Saputra et al., 2025)
Coconut shell activated carbon	700ºC for 2 h; 2.5 M KOH for 20 h	Rhodamine B 20 ppm	1212.02	86.13%	This study

In the study conducted by Yu (2024), the adsorption of Rhodamine B was carried out using coconut shell activated physically at 600 °C for 2 hours and chemically with 2 M H_3PO_4, resulting in a surface area of 408.59 m^2/g. Meanwhile, in the study by Yang & Han (2018), the adsorption of lysine was performed using coconut shell activated with KOH, yielding a BET surface area of 1118.2 m^2/g. Therefore, the development of the previous study was to increase the KOH concentration, with coconut shell charcoal adsorbent that was physically activated at 700 °C for 2 hours and chemically with 2.5 M KOH.

In this study, coconut shell charcoal activated physically at 700 °C for 2 hours and chemically activated using 2.5 M KOH solution is able to achieve a surface area of 1212.02 m^2/g. This activation condition effectively increases the surface area of the adsorbent 3 times greater than the surface area value that has been carried out by Yu (2024). The concentration of Rhodamine B used in this study was 20 ppm, which is higher than the research concentration presented in Table 2 and produces an adsorption efficiency of 86.13%. Although this value is lower, the use of a higher dye concentration in this study provides a more reflective picture of the actual conditions in wastewater contaminated with Rhodamine B.

4. Conclusions

The results of this study demonstrate that coconut shell charcoal activated physically using a furnace and chemically with 2.5M KOH is effective in reducing the concentration of Rhodamine B. Under ambient temperature conditions, with a contact time of 120 minutes at equilibrium and using 3 g of adsorbent, the Rhodamine B concentration was reduced with an efficiency of 86.13%, achieving a final concentration of 2.72 ppm. Adsorption isotherm analysis shows that the adsorption process follows the Langmuir model, with R^2 value of 0.97. Based on the RL value, the adsorption process in this study is favorable because it can be controlled under certain conditions and adsorption occurs normally. Furthermore, the interaction between the adsorbate and the adsorbent occurs in the form of monolayer adsorption.

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List of Notations:

Q_e = Capacity adsorption at the time equilibrium (mg/g)
C_e = Concentration of adsorbate at the time equilibrium (mg/L)
C_o = Initial concentration adsorbate (mg/L)
C_t = Concentration of adsorbate at time t (mg/L)
m = Mass of adsorbent (g)
V = Volume of solution (L)
Q_{max} = Capacity adsorption maximum (mg/g)
K_L = Constant Langmuir isotherm (L/mg)
R_L = Langmuir separation factor
K_F = Constant Freundlich isotherm (L/mg)
n = Degree of non- linearity
K_H = Constant Halsey isotherm
K_J = Constant Javanovic isotherm (L/mg)
K_{FH} = Constant Flory isotherm (L/mg)
E_t = Efficiency adsorption at times t (%)
E_e = Efficiency adsorption equilibrium (%)
t = time (min)