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Biochar from *Kapuk Randu* (*Ceiba pentandra*) Seeds for Adsorption of Remazol Blue Dye in Wastewater

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Abstract. The use of synthetic dyes such as remazol by textile companies can harm the environment because they are toxic, long-lasting, and hard to break down. This study aims to find out how well biochar made from *randu kapuk* seeds can absorb colors in water by determining the best weight, contact time, and pH level. The study's findings indicate that the moisture content of biochar made from *randu kapuk* seeds at temperatures of 400°C, 450°C, and 500°C is 5.7%, 5.1%, and 4.3%, respectively. The ash concentration at temperatures of 400℃, 450℃, and 500℃ was 7.7%, 6.8%, and 6.3%, respectively. The best amount of biochar tested was 100 mg, which could absorb 25 mg of remazol Blue, giving it an adsorption capacity of 1.65 mg/g. The best time for biochar made from *kapuk* seeds to absorb remazol Blue was 30 minutes, with an absorption ability of 1.59 mg/g. The optimal pH for the adsorption of remazol Blue was 4, with a capacity of 5.39 mg/g. The results showed that biochar made from *kapuk* seeds was excellent at soaking up substances and followed certain patterns that suggest it works through a single layer of chemical bonding. This study highlights how effective biochar made from *kapuk* seeds is as a safe and eco-friendly material for cleaning dye-polluted water, which helps promote sustainable water management in line with SDG 6: clean water and sanitation.
Keywords: Kapuk Randu Seeds, Biochar, Remazol blue and Adsorption

Introduction

The swift growth of the textile industry has resulted in a substantial rise in dye-contaminated wastewater, presenting grave environmental and public health issues. Among the diverse array of dyes, remazol dyes—specifically remazol Brilliant Blue and its derivatives—are recognized for their exceptional solubility, stability, and resilience to standard biological treatment methods. If discharged untreated, these dyes can diminish light penetration in aquatic environments, obstruct photosynthesis, and induce toxicity in aquatic creatures.

Adsorption is considered one of the most effective and cost-efficient techniques for dye removal, owing to its simplicity, efficacy, and adaptability to diverse wastewater conditions. Recently, focus has transitioned to the creation of sustainable, economical adsorbents sourced from agricultural waste. *Kapuk* seed (*Ceiba pentandra*) biomass is a promising material that is plentiful in tropical locations and significantly underutilized.

Kapuk is a natural fiber extracted from its fruit. *Kapuk* is known for its extremely light weight and flammability. Another name for this plant is *Ceiba pentandra*. The *kapuk* plant grows in tropical regions at elevations up to 700 meters above sea level. Communities primarily utilize *kapuk* fiber as a material for making pillows and mattresses, while the seeds of the *kapuk* plant have yet to be fully utilized by communities. The seeds contain cellulose (21.83%), hemicellulose (23.24%), lignin (10.37%), and other chemical components. *Kapuk* seeds have potential as raw material in the manufacture of adsorbents because they contain a significant amount of carbon (Wahyuni et al., 2017). Thus, *kapuk* seeds are one of the available low-cost biomass waste products that can be used as adsorbents to reduce water pollution problem. Biochar is a carbon-dense substance characterized by its extensive surface area, functional groups, and porous structure, rendering it effective for the adsorption of organic contaminants, including synthetic colors. The use of biochar obtained from *kapuk* seeds effectively removes dyes, promotes waste valorization, and adheres to circular economy principles.

Dyes in wastewater can be caused by community activities, industrial development, and increased agricultural activities (Radwan et al., 2022). Dye pollution in water is a major global environmental problem due to the disposal of untreated colored wastewater (Srivatsav et al., 2020). Colored waste from small industries such as the batik industry, which do not have proper treatment facilities at the end of the process, can pose a serious threat due to its toxic, carcinogenic, and mutagenic properties (Meskel et al., 2024). Synthetic dyes are one of the causes of water pollution, because once they enter the water, they are difficult to degrade due to their complex synthetic compounds, which are designed to be resistant to light, chemical and biological reactions, and high concentrations of colored waste, making them difficult to remove (Amelia et al., 2023).

Biochar is a solid material rich in carbon that is made by burning organic material at high temperatures without oxygen, a process called pyrolysis (Nworie et al., 2019). Many studies have looked at using biochar made from agricultural waste to soak up dyes, such as biochar from rice husks to remove rhodamine B dye, from Ketapang shells for naphthol yellow, from coconut husks for indigosol Blue dye, and recently, from *kapuk* tree branches for Naphthol Yellow. Besides dye absorption, biochar derived from agricultural waste has been extensively utilised, including corn stalks for the adsorption of BOD and COD in hospital effluent (Walanda et al., 2022), dried cocoa leaves as adsorbents to enhance tofu wastewater quality (Malik et al., 2023), and sunflower petals for cadmium absorption from solutions (Somba et al., 2024).

This study examines the synthesis and adsorption efficacy of biochar derived from *kapuk* randu seeds for the elimination of remazol dye from wastewater. This research enhances sustainable water treatment options by examining the efficiency, mechanism, and prospective applications of the bio-based adsorbent, thereby supporting worldwide initiatives to achieve the objectives of SDG 6.

Methods

The raw material for biochar is derived from the abundant and unusable seeds of *Ceiba pentandra*. Remazol blue is used in the laboratory as a synthetic solution with a specific concentration to make the condition more representative with regard to the textile waste. The *kapuk* seeds were sun-dried for 24 hours following a wash and further drying in an oven at 105°C for 1 hour (Wahyuni et al., 2017). The desiccated *kapuk* seeds underwent pyrolysis at temperatures of 400, 450, and 500°C for one hour, thereafter cooling to ambient temperature. The samples were subsequently pulverised with a mortar and pestle and filtered through an 80-mesh screen (Napitupulu et al., 2025). Following the production of biochar, its properties were evaluated, including moisture content, ash content, pore morphology via scanning electron microscopy (SEM), elemental composition analysis through energy dispersive X-ray spectroscopy (EDS), functional group assessment using fourier transform infrared spectroscopy (FTIR), and dye removal efficiency in water, which was determined by optimising concentration with variations in weight, contact time, and pH, analysed using UV-Vis spectroscopy. The adsorption outcomes for each modification were determined utilising the formulas for adsorption capacity (Qe) and adsorption efficiency (% adsorption) (Napitupulu et al., 2020).

$$Qe = \frac{(Ci - Ceq)V}{m} \quad (1)$$

$$\%\ Adsorbed = \frac{Ci - Ceq}{Ci} \times 100\% \quad (2)$$

Explanation:
Qe : Adsorption capacity (mg/g)
Ci : Initial concentration (mg/L)
Ceq : Final concentratiom (mg/L)
V : Volume (L)
m : Mass (g)

To determine the maximum adsorption capacity and monolayer properties, the Langmuir isotherm model is used. While the Freundlich Isotherm model was used to determine the heterogeneity of the biochar surface.

Results and Discussion

The biochar production method commences with sample preparation, wherein *kapuk* seeds are initially cleansed with running water and sun-dried for 24 hours, followed by additional drying in an oven at 105°C for 1 hour. This is performed to diminish the moisture content in the *kapuk* seed debris produced following washing. The desiccated *kapuk* seeds undergo pyrolysis in a furnace at temperatures of 400, 450, and 500°C for a duration of 1 hour Elevating the pyrolysis temperature enhances the porosity of biochar, consequently augmenting its adsorption capability (Edwin et al., 2023). The cotton seed biochar is further pulverised and sieved through an 80-mesh sieve to diminish the particle size, hence enhancing the active surface area. This facilitates the absorption of more adsorbates (Wahyuni et al., 2017).

The determination of moisture content is conducted to ascertain the quantity of water present in the biochar. Simultaneously, ash content analysis was performed to ascertain the quantity of minerals retained in the biochar post-pyrolysis. Residual minerals may obstruct the pores of biochar, thereby diminishing its adsorption capacity (Suprabawati et al., 2018). Table 1 presents the results regarding the moisture content and ash content of *kapuk* seed biochar.

Table 1. Water and ash content of biochar from *kapuk* seeds

Pyrolisis temperature (°C)	Water content (%)	SNI (%)	Ash content (%)	SNI (%)
400	5.7	15	7.7	10
450	5.1	15	6.8	10
500	4.3	15	6.3	10

Table 1 presents the moisture and ash content derived from *randu kapuk* seed biochar. The moisture and ash content measured comply with the SNI 06-3730-1995 norm. Prolonged pyrolysis results in reduced moisture content. The ash content has an inverse relationship with pyrolysis temperature; as the temperature increases, the ash content decreases. At elevated temperatures, more combustion transpires, resulting in the depletion of organic material, hence influencing the ash concentration (Roshan et al., 2023). This work aligns with the research by Rahim et al. (2022) regarding activated charcoal derived from *kapuk* seeds as an adsorbent for copper metal, indicating that reduced moisture content enhances the charcoal's quality by increasing its adsorption capacity for gases or liquids. The smaller the water molecules within the charcoal, the lesser the impediment for other molecules to penetrate. The ash content in biochar influences charcoal quality, as an extremely high ash content may obstruct the pores of the biochar, hence diminishing the surface area. A reduced ash percentage in biochar enhances its capacity to absorb colour molecules.

The microstructural properties of biochar were analysed to determine pore morphology utilising SEM. Figure 1 illustrates the pore morphology of *randu kapuk* seed biochar at 500°C, with magnifications of 1000x, 3000x, 5000x, and 10000x.

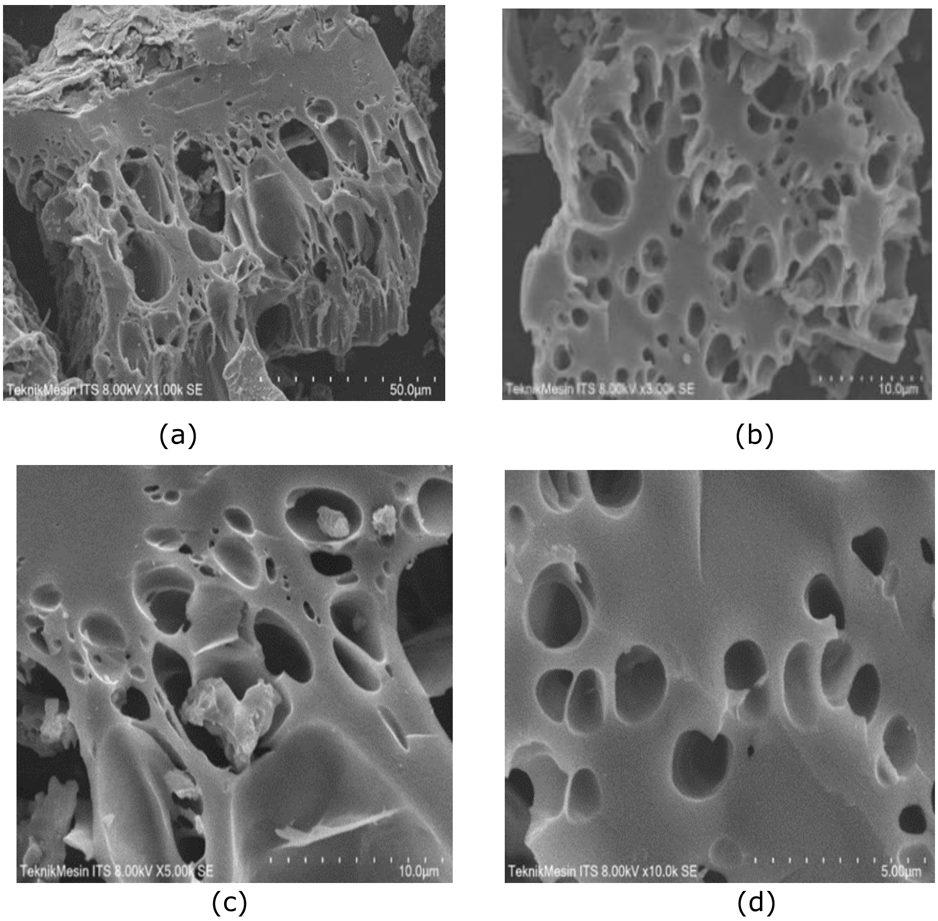

Figure 1. SEM examination of *kapuk* seed biochar at 500°C with magnifications of (a) 1000x, (b) 3000x, (c) 5000x, and (d) 10000x

Adsorbents are classified into three categories based on pore size: micropores (pore sizes below 1 nm), mesopores (pore sizes ranging from 1 to 25 nm), and macropores (pore sizes beyond 25 nm). Mesopores facilitate the retention of ingested substances and act as an access point to micropores. Macropores facilitate the rapid transport of adsorbate molecules to smaller, deeper pores inside the material, whereas micropores are paramount in the adsorption process (Alimah, 2021).

Figure 1 illustrates the SEM surface of *randu kapuk* seed biochar at different magnification settings. The biochar derived from *randu kapuk* seeds possesses many pores on its surface, exhibiting diverse sizes and irregular configurations. This signifies the presence of many active sites for adsorbate binding, hence enhancing the adsorption ability of *randu kapuk* seed biochar for remazol blue. Pore formation results from the evaporation of volatile chemicals from the raw material during the pyrolysis process (Malik et al., 2023).

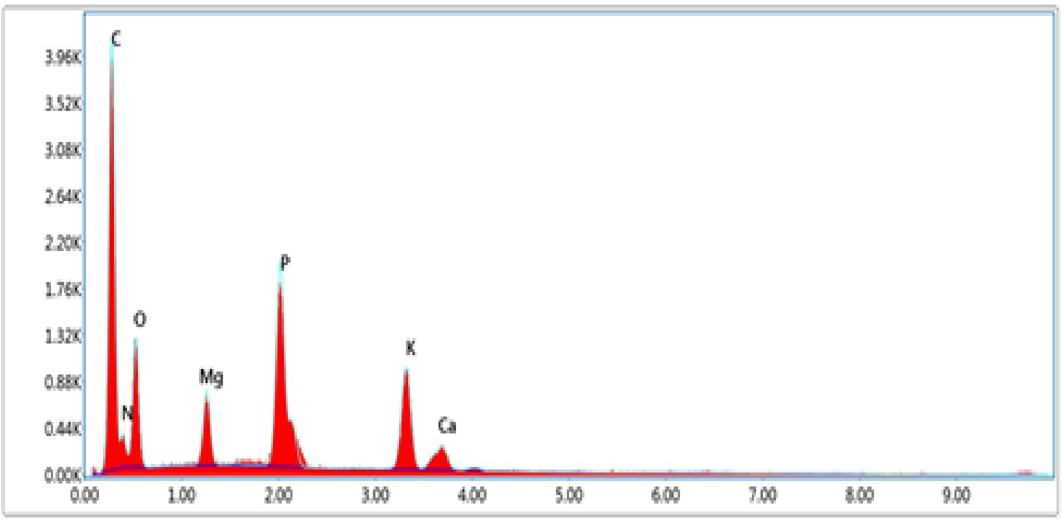

Figure 2. EDS spectra of biochar from *randu kapuk* seeds

Figure 2 indicates that *randu kapuk* seed biochar comprises the following elements: carbon 56.24%, nitrogen 11.69%, oxygen 20.33%, magnesium 2.00%, phosphorus 5.09%, potassium 3.53%, and calcium 0.99%. The bound carbon content that complies with the SNI 06-3730-1995 standard is an adsorbent containing 65% bound carbon. In this study, the carbon content of *randu kapuk* seed biochar is less than 65%. This tendency aligns with the research conducted by Malik et al. (2023). The low carbon concentration suggests that the manufactured adsorbent has relatively low purity, as its surface still harbours non-carbon molecules, leading to subpar adsorbent quality. High pyrolysis time and temperature lead to excessive oxidation, with elevated temperatures exacerbating oxidation and oxidising gases compromising pore walls, hence diminishing pore surface area and reducing carbon content (Lestari et al., 2017). Functional groups were examined via FTIR within the wavenumber range of 3000–1000 cm^{-1}. This investigation is significant as the characteristics of an adsorbent are influenced not only by its pore size but also by its chemical makeup (Nurhasni et al., 2018). Figure 3 illustrates the outcomes of the biochar spectrum investigation of *kapuk* seeds at 500°C.

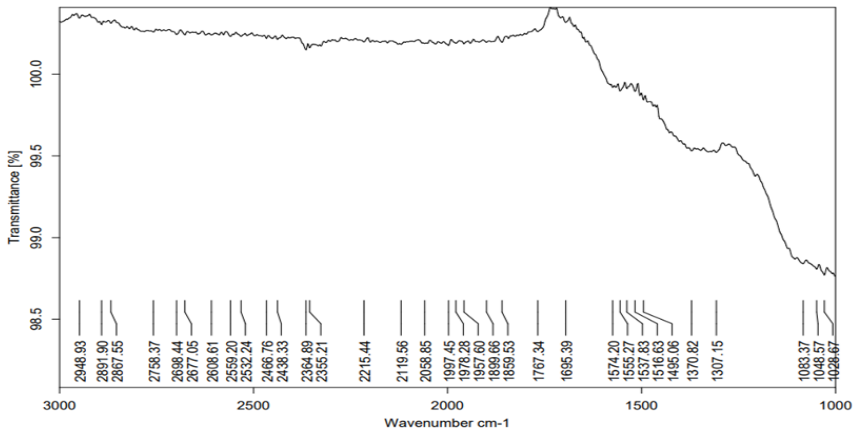

Figure 3. FTIR spectra of biochar from *randu kapuk* seeds

Figure 3 illustrates that *randu kapuk* seed biochar displays wavelengths ranging from 1767.34 cm^{-1} to 1695.39 cm^{-1}, signifying the existence of C=O groups, and absorption peaks between 1574.20 cm^{-1} and 1495.06 cm^{-1}, suggesting aromatic C=C groups. The C=O (carbonyl) group is indicative of activated carbon, hence biochar derived from *kapuk* seeds is applicable in adsorption processes (Rizki et al., 2019).

The biochar's weight was assessed to ascertain if increasing the quantity of biochar would enhance its adsorption capacity for remazol blue, utilising four distinct weights derived from *kapuk* seeds.

Table 2. Concentration of rermazol blue in different weights of *randu kapuk* seed biochar

Biochar Weight (mg)	Time (min)	Abs	Ci (mg/L)	Ceq (mg/L)	Cb (mg/L)	Qe (mg/g)
25	60	0.705	15	10.86	4.14	1.65
50	60	0.682	15	10.43	4.57	0.91
75	60	0.723	15	11.19	3.81	0.50
100	60	0.768	15	12.04	2.96	0.29

Table 2 indicates that an increase in the quantity of adsorbent results in a reduction of its adsorption capability. The adsorption of remazol blue dye solution is maximal at a weight of 25 mg, yielding an adsorption quantity of 1.65 mg/g; however, at weights of 50 mg, 70 mg, and 100 mg, the adsorption capacity diminishes. Typically, augmenting the bulk of the adsorbent should improve pollutant adsorption, thus elevating the removal percentage. In this study, an increase in the quantity of adsorbent correlates with a decrease in dye absorption. The reduction in absorption with the augmentation of adsorbent mass results from the saturation of active adsorption sites and the aggregation of adsorbent particles, leading to a diminished overall surface area. Particle aggregation may induce the desorption of poorly bound adsorbates from the adsorbent surface (Anwar et al., 2022). Prior investigations into activated charcoal derived from *kapuk* seeds as an adsorbent for lead (Pb) demonstrated that an augmentation in the quantity of adsorbent corresponded with enhanced adsorption, since a greater amount of adsorbent provides more active sites for charcoal interaction (Wahyuni et al., 2017).

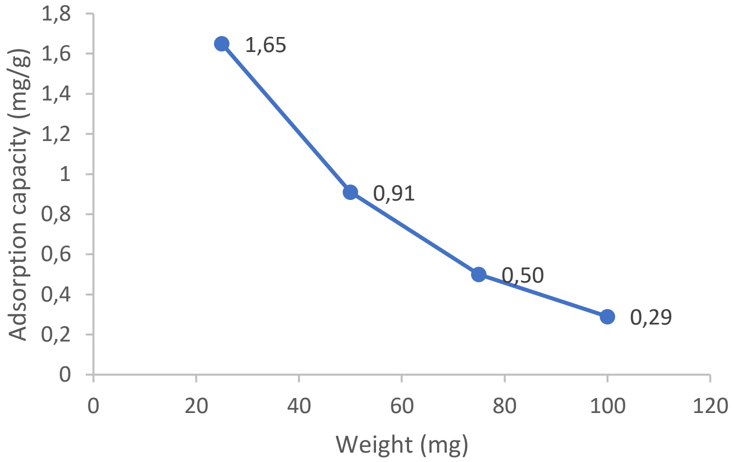

Figure 4. Graph illustrating the correlation between biochar mass and remazol blue adsorption capacity

The contact duration for *randu kapuk* seed biochar was assessed using five distinct time intervals to adsorb remazol blue. The contact time measurement results for *kapuk* seed biochar is presented in Table 3.

Table 3. Remazol blue concentration at various contact times with randu seed biochar

Biochar Weight (mg)	Time (min)	Abs	Ci (mg/L)	Ceq (mg/L)	Cb (mg/L)	Qe (mg/g)
25	20	0.795	15	12.54	2.46	0.98
25	30	0.714	15	11.02	3.98	1.59
25	40	0.763	15	11.94	3.06	1.22
25	50	0.734	15	11.40	3.6	1.44
25	60	0.809	15	12.80	2.2	0.88

Table 3 illustrates a fluctuation in the adsorption capacity of the adsorbent. Initially, during the first 20 to 30 minutes of contact time, there was an increase in adsorption capacity, followed by a decline between 40 and 60 minutes of contact time. As contact duration extends, the quantity of dye adsorbed rises; however, once reaching the optimal threshold, the amount of dye adsorbed thereafter declines. This suggests that prolonged contact time leads to the desorption of the adsorbate as the adsorbent surface attains saturation (Lestari et al., 2020).

The rising efficiency of dye adsorption subsequently diminishes due to the equilibrium process or saturation level between the adsorbate and adsorbent at the contact time, where nearly all active sites on the adsorbent have interacted with the adsorbate, rendering additional contact time ineffective. This occurrence signifies that physical adsorption is reversible owing to the weak link between the adsorbent and the coloured substance, permitting the substance to re-enter the solution as contact time extends (Anwar et al., 2022). A prior investigation into rice husk adsorbents for the adsorption of rhodamine B dye (Sugiharto et al., 2020) indicated that the optimal contact time is observed at the onset of adsorption. This is evidenced by the increase in adsorption capacity, as the initial phase of adsorption exhibits a rapid rate due to the complete availability of the pore surface, allowing dye molecules to adhere and establish a layer on the surface. As time progresses, the adsorption capacity diminishes due to the reduction of available pore surfaces, consequently impairing the adsorbent's ability to capture dye molecules.

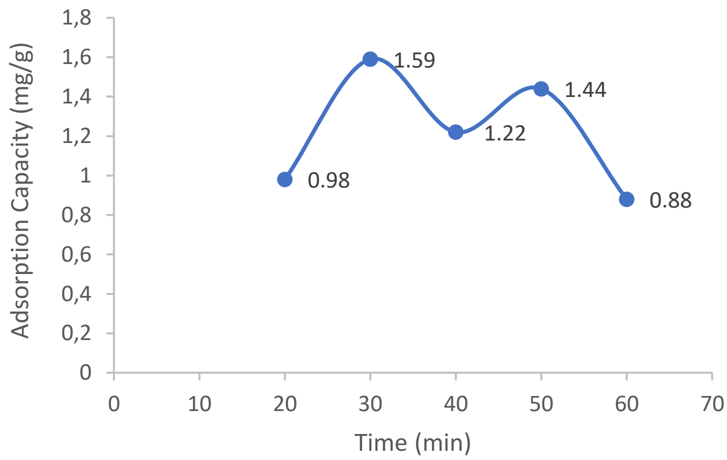

Figure 5. The correlation between contact duration and the adsorption capability of remazol blue

The optimal pH was established to assess the impact of acidity on the adsorption of remazol blue. The pH measurement data is presented in Table 4.

Table 4. Concentration of remazol blue in charcoal derived from *kapuk* seeds at several pH values

Biochar Weight (mg)	Time (min)	pH	Abs	Ci (mg/L)	Ceq (mg/L)	Qe (mg/g)
25	30	4	0.206	15	1.51	5.39
25	30	7	0.648	15	9.79	2.08
25	30	10	0.623	15	9.32	2.27

According to the data in Table 4, optimal adsorption of remazol blue occurs at pH 4, while adsorption diminishes at pH 7 and 10. Beginning at a low pH (acidic circumstances), an increase in pH correlates with a rise in the quantity of coloured solution adsorbed. Once the pH value surpasses the near-equilibrium level (alkaline circumstances), the quantity of coloured solution adsorbed diminishes (Fitriansyah et al., 2021).

The adsorption of organic materials from wastewater often rises with a fall in pH. Under acidic conditions, the dye experiences deprotonation, and upon the introduction of cellulose to the coloured solution, the cellulose surface initially receives protonation, subsequently leading to electrostatic interactions that drive the dye in the solution towards the protonated adsorbent. At acidic pH, the negative charge on the adsorbent surface neutralises, resulting in increased protonation and enhanced adsorption capacity. This situation enhances diffusion, consequently augmenting the quantity of active sites on the adsorbent surface. Furthermore, H^+ ions in the solution may function as ligands, facilitating the connection between the adsorbent and the dye molecules (Nika et al., 2022).

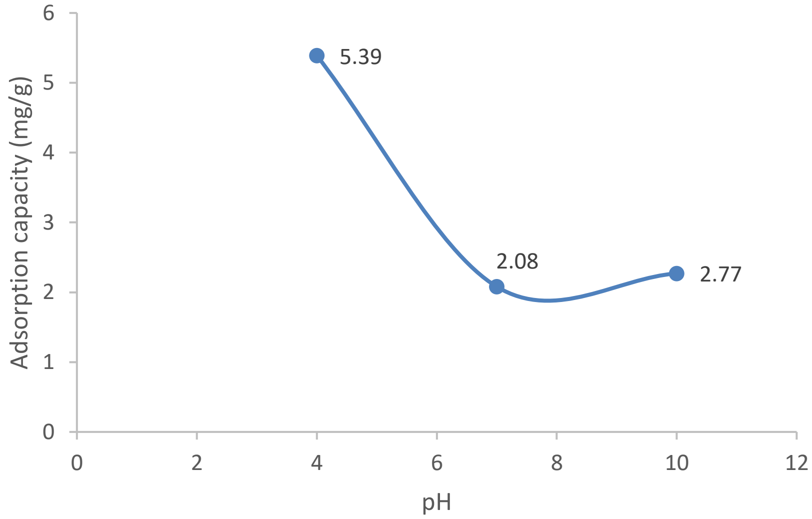

Figure 6. The graph illustrating the correlation between pH fluctuations in solution and the adsorption capability of remazol blue.

Adsorption isotherms delineate the quantity of a solute adsorbed onto a solid and the equilibrium concentration of the solute in the solution under specified conditions. The predominant isotherms utilised in the application of activated carbon for wastewater treatment are the Langmuir and Freundlich isotherms (Ouedrhiri et al., 2022). Table 5 presents measurement data for Langmuir and Freundlich isotherms at different pH values.

Table 5. Langmuir and Freundlich adsorption isotherms at different pH values of randu seed biochar.

pH	Ceq (mg/L)	Ce (mg/g)	Ceq/Ce	Log Ceq	Log Ce
4	1.51	5.39	0.28	0.17	0.73
7	9.79	2.08	4.70	0.99	0.31
10	9.32	2.27	4.10	0.96	0.35

The Langmuir isotherm delineates the adsorption process occurring in a monolayer, characterised by homogeneous surface sites, where each active site can adsorb only one molecule (Amelia et al., 2023). The Freundlich isotherm elucidates that the adsorbent surface is heterogeneous, facilitating the production of many adsorption layers and the existence of active adsorption sites with high affinity, while other regions exhibit low affinity. This enables the adsorbate to migrate freely, resulting in the formation of numerous layers (Fitriansyah et al., 2021). The adsorption process data for biochar at different pH levels were examined using a linear equation to generate a curve depicting the relationship between Ceq/Ce and Ceq, representing the Langmuir isotherm curve, while the curve illustrating the relationship between Log Ce and Log Ceq represents the Freundlich isotherm curve. Figures 7 and 8 illustrate the Langmuir and Freundlich isotherm models derived from the pH variation data for biochar produced from *kapuk* seeds.

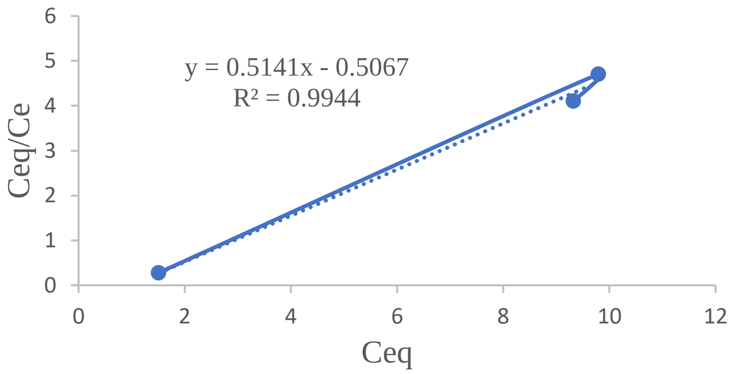

Figure 7. Langmuir linearity curve for the adsorption of remazol blue dye at different pH levels.

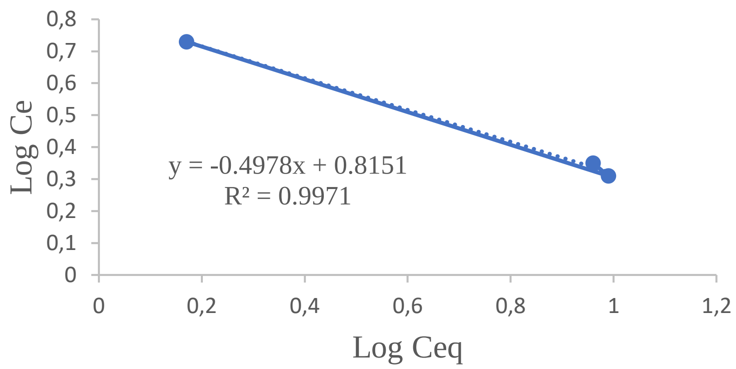

Figure 8. Freundlich linearity curve for the adsorption of remazol blue dye across different pH levels.

A comparison of R^2 values was conducted, as illustrated in Figures 7 and 8, to identify the more appropriate isotherm for the adsorption process on *kapuk* seed biochar. An R^2 value nearing 1 signifies a stronger influence and suggests a more favourable interaction between factors (Fitriansyah et al., 2021). Upon comparison of the R^2 values on the linearity curve above, the Freundlich isotherm model exhibits a superior R^2 value, approaching 1 (0.9971), in contrast to the Langmuir isotherm model. The adsorption of remazol blue using biochar derived from *kapuk* seeds aligns more closely with the

Freundlich isotherm model, indicating that the adsorption process entails the development of multiple layers on the adsorbent surface (multilayer), which substantially enhances the overall adsorption capacity (Fitriansyah et al., 2021).

Conclusion

This work illustrates that biochar derived from *kapuk* seeds (*Ceiba pentandra*) possesses significant promise as a natural adsorbent for the removal of remazol dye from textile effluent. The pyrolysis process yields biochar with physical and chemical properties conducive to adsorption, including adequate surface area, favourable pore structure, and the presence of active functional groups. The study concludes that differences in weight, contact time, and pH influence the adsorption of remazol blue utilising biochar derived from *kapuk* seeds. The optimal conditions for the adsorption of remazol blue were achieved with a biochar weight of 25 mg, a contact period of 30 minutes, and a pH of 4. The utilisation of biochar derived from agricultural waste, such as *kapuk* seeds, offers a novel approach for the remediation of coloured wastewater while promoting sustainability and the circular economy. This work directly supports target 6.3 of sustainable development goal (SDG) 6 by diminishing the concentration of deleterious organic pollutants in wastewater, hence enhancing water quality through pollution reduction, waste disposal elimination, and the minimisation of hazardous chemical release.

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