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Efficient Removal of Indigosol Blue Using Activated Carbon from Kepok Banana (Musa paradisiaca x balbisiana) Peels

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Abstract: Indonesia's textile industry has experienced significant growth, yet it faces environmental challenges from dye waste, such as Indigosol Blue, which is classified as hazardous and toxic, requiring special treatment. The use of activated carbon in the adsorption process has proven effective, and the Kepok banana (Musa paradisiaca x balbisiana) peel, with its high cellulose content, is a potential raw material for activated carbon. This research aims to produce adsorbents from Kepok banana peel, activated by HCl, to adsorb Indigosol Blue using an adsorption column. The production of activated carbon was conducted through carbonization and activation processes. HCl with a concentration of 37% was used as the activator, where the soaking process lasted for 24 hours, and the activation temperature was set at 90°C for 120 minutes. The activated carbon was characterized using UV-Vis Spectrophotometry, Scanning Electron Microscopy (SEM) and Fourier Transform Infrared (FTIR). Based on the results of SEM analysis that illustrates the differences in topography and morphology of kepok banana peel powder before and after activation using various concentrations of activating agents. The results of FTIR analysis, the presence of O-H and C-O bonds indicates that activated carbon derived from kepok banana peel has more polar characteristics. If the initial colorant is increased resulting in higher adsorption efficiency. The results of this study indicated that the optimal wavelength for the Indigosol Blue dye solution, was 624 nm. The best adsorption efficiency was 88.5%, and the maximum adsorption capacity of 0.24 mg/g was obtained with an adsorbent concentration of 30 ppm.

Keywords: adsorption, activated carbon, Kepok banana (Musa paradisiaca x balbisiana) peel, Indigosol Blue dye

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1. Introduction

The textile industry holds a central position as one of the rapidly growing industrial sectors. Globally, the textile industry generates approximately 700 tons of dye waste each year (Munasir & Ramadiani, 2023). The negative impact of the textile industry's growth has led to environmental changes through pollution processes. The textile industry is a major contributor to waste in aquatic ecosystems, with the production of dye waste posing potential hazards to living organisms. These

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wastes will continue to be generated in large quantities as the textile industry grows. The complex aromatic chemical compounds present in dye waste inhibit the ability of microbes to decompose, often making biological degradation processes difficult. The presence of dye waste also poses health risks to humans (Irawati *et al*., 2018). Various types of dyes and solvents used in the textile industry have been shown to possess mutagenic and carcinogenic properties when in direct contact with the skin (Oktaviani and Risanti, 2022).

Indigosol Blue is a synthetic pigment commonly used in the textile industry due to its low cost and aesthetic properties. However, according to Government Regulation No. 19 of 1994, waste from the textile industry is classified as hazardous and toxic waste (B3), which refers to industrial or human activity residues that pose a threat to environmental sustainability (Kusuma, 2024). Indigosol Blue contains toxic and carcinogenic substances that pose dangers to both humans and the environment. Treatment processes are required before this waste can be released into the environment. Various technologies have been employed to treat wastewater containing dyes, including reverse osmosis, coagulation, membrane filtration, ozonation processes, chemical oxidation, and biosorption (Septiariva *et al*., 2021). One of the strategies that can be applied to mitigate pollution from the textile sector is the adsorption technique. The adsorption approach has proven efficient in eliminating waste pigments derived from dye compounds.

Activated carbon is frequently used as a common adsorbent due to its larger surface area compared to other adsorbents. The production of activated carbon can be carried out from various carbon-containing materials, especially those with significant cellulose content (Fitriansyah *et al*., 2021). Agricultural waste has significant potential to advance wastewater treatment technology due to its abundant availability in the natural environment and the relatively low cost of obtaining it. Additionally, it contains several biochemical elements such as cellulose, hemicellulose, chlorophyll pigments, and pectin substances (Arifiyana and Devianti, 2020).

One material with high cellulose content is the banana peel (Musa paradisiaca L.), which contains several chemical elements, including nitrogen, sulfur, and organic substances such as carboxylic acids, cellulose, hemicellulose, chlorophyll pigments, and pectin components containing galacturonic acid, arabinose, galactose, and rhamnose. In general, banana peels are not fully utilized and are often used only as animal feed or discarded. One variety of banana peels with high cellulose content is the Kepok banana peel (Musa paradisiaca x balbisiana). Kepok banana peels have a higher carbon content compared to other banana varieties, amounting to 44.2% (Septiana, 2023). Kepok banana peels are easier to process into activated carbon, even with simple methods, and they are one of the most commonly consumed varieties in Indonesia (Widyaningsih, 2022). According to the Indonesian Ministry of Agriculture in 2021 (Kementerian Pertanian Republik Indonesia, 2021), the production of Kepok bananas in Indonesia reached 2.5 million tons. With banana peel waste accounting for 20-30% of the total, the amount of Kepok banana peel waste generated is approximately 500,000 to 750,000 tons per year.

Previous studies have indicated that Kepok banana peels are capable of adsorbing methylene orange dye at a rate of 94.2370% with a contact duration of 120 minutes, using 0.15 M HCl as the activator, and an adsorption capacity of 0.0283 mg/g in a batch process (Budiawan, 2021). Based on this background, this research will utilize Indigosol Blue dye as the adsorbed substance in an adsorption column method, as this method offers greater adsorption capacity, higher adsorption efficiency, and can be operated continuously. This research contributes to improving existing methods by evaluating the use of activated carbon from Kepok banana peels in a column adsorption method. Additionally, this research emphasizes sustainability in wastewater treatment by utilizing agricultural waste as a low-cost and easily obtainable adsorbent. The key experimental conditions in this study include optimizing adsorbent mass and contact time to achieve maximum adsorption efficiency.

The aim of this study is to evaluate the effectiveness of Kepok banana peel carbonization in absorbing Indigosol Blue dye. Additionally, this research seeks to analyze the influence of variations in adsorbent mass and contact time on the adsorption capacity of the dye. Furthermore, this study systematically demonstrates that the column adsorption method exhibits higher efficiency compared to other methods in the absorption process of Indigosol Blue.

2. Materials and Method

The research was conducted from April to July 2024 at the Integrated Laboratory Unit of UNS, the Biology Laboratory of the Faculty of Mathematics and Natural Sciences (FMIPA) UNS, and the Integrated FMIPA Laboratory UNS. The equipment used included glassware, pestle and mortar, an analytical balance, an oven, and an adsorption column measuring 6 cm in width and 50 cm in height. The characterization instruments used were a UV-Vis Spectrophotometer (Hitachi UH5300, Japan), Fourier Transform Infrared (FTIR, Shimadzu Prestige-21), and Scanning Electron Microscopy (SEM, JEOL_JSM_6510). The materials used were kepok banana peel, distilled water, HCl, Indigosol Blue dye, and aluminum foil.

2.1 Preparation of Activated Carbon from Kepok Banana Peel

The production of activated carbon from kepok banana peels aims to activate the carbon by expanding its pores through high-temperature heating, thereby increasing the surface area of the carbon. The kepok banana peels are washed and sun-dried for two days. After drying, the banana peels are cut into approximately 2 cm pieces (Saputro *et al.*, 2023). A total of 250 grams of dried banana peels are placed in a 1000 ml beaker, followed by the addition of 1000 ml of HCl solution with varying concentrations of 0.15 M, 0.2 M, and 0.25 M, for a duration of 24 hours. After soaking, the banana peels are filtered and rinsed with distilled water until reaching a neutral pH level. Next, the banana peels are activated in an oven at 90°C for 12 hours.

2.2 Preparation of Indigosol Blue (C16H10N2O2S) Dye Solution

The preparation of the Indigosol Blue (C16H10N2O2S) dye standard solution was carried out with meticulous and precise procedures. The first step involved weighing the Indigosol Blue powder using an analytical balance to ensure accuracy. After weighing, the obtained masses of the Indigosol Blue powder were 15 mg, 20 mg, 25 mg, and 30 mg. The powder was then dissolved in distilled water to a total volume of 1 liter. As a result, the concentrations of the resulting solutions were 15 ppm, 20 ppm, 25 ppm, and 30 ppm.

2.3 Adsorption of Indigosol Blue (C16H10N2O2S) Dye by Activated Carbon from Kepok Banana Peel

The Adsorption Test of Indigosol Blue (C16H10N2O2S) Dye was conducted in a glass aquarium with a rectangular shape, having a diameter of 6 cm and a height of 50 cm. In the initial stage, the adsorbent, which had been activated with HCl solution in concentrations of 0.15 M, 0.2 M, and 0.25 M, was placed in the glass aquarium in the amount of 250 grams with contact times of 60 minutes and 120 minutes. Indigosol Blue (C16H10N2O2S) solution with concentrations of 15, 20, 25, and 30 ppm was flowed downwards through the column. Samples of the solution exiting the adsorption column were collected according to the predetermined contact times. The adsorption process results were then analyzed using UV-Vis and FTIR spectrophotometers.

2.4 Determination of the Optimum Wavelength (λ) of Indigosol Blue Dye

Standard solutions of Indigosol Blue (C16H10N2O2S) dye were produced with varying concentrations of 15, 20, 25, and 30 ppm. Subsequently, the optimum wavelength (lambda) of Indigosol Blue dye was determined using spectrophotometry with a UV-Vis spectrophotometer. First, 10 mL of the Indigosol Blue dye solutions at concentrations of 15, 20, 25, and 30 ppm was taken using a micropipette. The absorbance of these solutions was then measured using the UV-Vis spectrophotometer. The absorbance measurements from the UV-Vis spectrophotometer can be taken in the visible wavelength area, specifically within the range of 400-760 nm. This wavelength determination aims to assess the absorption rate in relation to the concentration of the solution.

2.5 Calibration Curve Creation Using UV-Vis Spectrophotometry

Standard solutions of Indigosol Blue dye were prepared with varying concentrations of 15, 20, 25, and 30 ppm by dissolving 15, 20, 25, and 30 mg of Indigosol Blue dye in a 1000 mL volumetric flask. The dye was then diluted with distilled water up to the mark and homogenized. Subsequently, the absorbance of the standard solutions of Indigosol Blue dye at these varying concentrations was measured using a UV-Vis spectrophotometer. Based on the absorbance data obtained, a standard curve was constructed, plotting the relationship between absorbance and concentration.

2.6 Data Analysis

The data from the variations in contact time and concentration were plotted to determine the optimum contact time and concentration using Excel software:

(a) Determination of Adsorption Capacity (Q):

$$Q = \frac{(C_0 - C_1) \cdot V}{M} \quad \text{.... Eq.1}$$

description:

Q = adsorption capacity (µg/g adsorbent)
C0 = initial dye concentration
C1 = dye concentration after adsorption
V = volume of solution (mL)
M = maximum adsorbent mass (g)

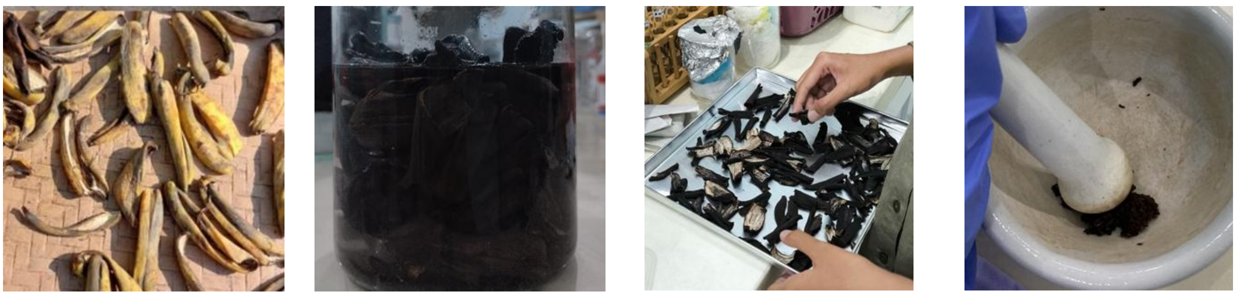
(b) Determination of Freundlich and Langmuir Parameters. The Freundlich parameters were determined by plotting the curve of log qe vs log Ce. The Langmuir parameters were determined by plotting the curve $\frac{Ce}{qe}$ vs Ce.

3. Result and Discussion

3.1. Production of Activated Carbon

Activated carbon derived from Kepok banana peels through the processes of carbonization and activation results in charcoal, as shown in Figure 1. The carbonization process produces charcoal from Kepok banana peels at a temperature of 90°C, over 12 hours. The activated carbon yield from the banana peels was 50% of the sample weight. From an initial 250 grams of sample, 125 grams of charcoal were obtained after the carbonization process. Temperature plays a significant role in the resulting charcoal. An increase in temperature leads to a reduction in the amount of charcoal formed, as some of the formed charcoal transforms into ash. However, the amount of liquid and gas produced tends to increase with the rise in temperature. Therefore, the temperature used needs to be adjusted according to the type of sample being analyzed.

To enhance the adsorption capacity of the charcoal, an activation process was conducted to expand the pores of the adsorbent. This process involves breaking hydrocarbon bonds or oxidizing surface molecules, which alters the physical and chemical properties of the charcoal. Consequently, the surface area of the adsorbent increases, which enhances the adsorption. The activation process involves the use of inorganic chemicals added to the raw material to reduce or eliminate organic compounds during carbonization or calcination.



(a) (b) (c) (d)

Figure 1. (a). raw materials before treatment, (b). After the carbo-nization process, (c). After the activation process, and (d) Powders used in the experiment.

This study utilized a chemical activation process by soaking the Kepok banana peels in a 37% HCl solution. Higher concentrations of the activating solution have a greater impact on binding the residual carbonization compounds, which are released through the micro-pores of the carbon (Qi *et al.*, 2021). This causes the carbon surface to become more porous, thereby increasing the adsorption capacity of the activated carbon (Heidarinejad *et al*., 2020). The following reaction occurs during the interaction of the activator with the charcoal in the solution:

HCl (aq) → H+(aq) + Cl-(aq)

During the activation process, H+ ions drive out non-volatile substances, such as alkali and alkaline earth ions, that remain on the surface of the charcoal. The high concentration of H+ ions replaces the alkali and alkaline earth ions bonded to the charcoal surface, releasing them. As a result, bonds between the carbon and H+ ions form on the surface of the activated charcoal.

This study involved soaking Kepok banana peels in an HCl solution for 24 hours. The soaking duration is one of the factors that influence the effectiveness of the activation process, as it affects the formation of lignin. The purpose of soaking in HCl is to dissolve the organic compounds in the charcoal, thereby opening the pores on the surface of the activated carbon and increasing its adsorption capacity.

After the 24-hour soaking period, the charcoal's color changed from dark gray to deep black. The charcoal was then filtered using Whatman filter paper to ensure that any remaining activator or residue was removed. Afterward, the drying process was carried out in an oven at 90°C for 12 hours. The purpose of this drying process was to reduce the remaining water content in the charcoal so that the final product was only activated carbon that had undergone the activation process.

3.2. Determination of the Optimum Wavelength (λ) of Indigosol Blue Dye

The determination of the optimal wavelength for the Indigosol Blue solution aims to find the wavelength used to measure the absorbance of the solution. At the optimal wavelength, maximum absorbance is achieved, allowing accurate measurements even when the solution has low or dilute concentrations.

Based on Figure 2, the optimal wavelength for Indigosol Blue is 624 nm. The wavelength range of 400-800 nm was selected because the complementary color of Indigosol Blue is blue, which has a light spectrum within the visible range between 500-650 nm (Fitriansyah *et al*.,2021). Therefore, the optimal wavelength was taken from that range and will be used in subsequent absorbance measurements using a UV-Vis spectrophotometer.

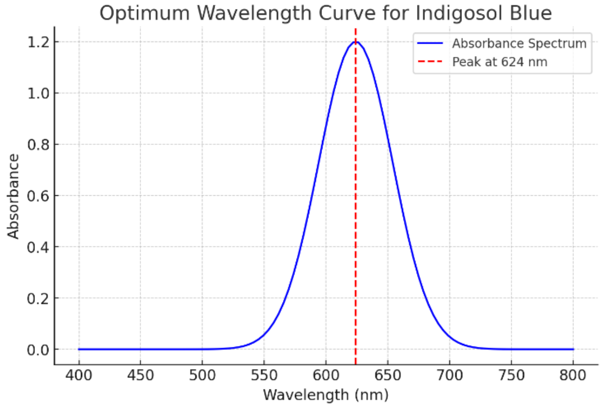


Figure 2. Curve for Determining the Optimal Wavelength for Indigosol Blue Solution

3.3 Preparation of the Standard Curve for Indigosol Blue Dye Solution

The calibration curve for varying concentrations, both high and low, was measured using the optimal wavelength. For the Indigosol Blue solution, the optimal wavelength is 624 nm.

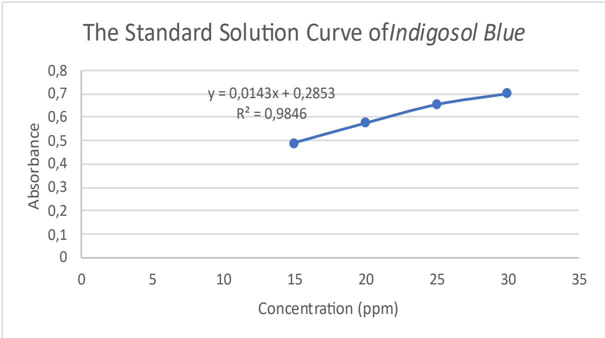


Figure 3. Calibration Curve for Indigosol Blue Solution

In Figure 3, the calibration curve shows the relationship between the concentration and absorbance of the Indigosol Blue solution at various concentration levels. The correlation coefficient (R^2) for the solution ranges from 0.9 to 1, meeting the criteria for a standard curve. The curve exhibits an excellent correlation, approaching a value of 1, and forms a straight line with a positive gradient. Therefore, the resulting regression equation can be used to measure the concentration of the dye solution during optimization processes as well as in subsequent adsorption activities.

3.4. Characterization of Activated Carbon using SEM

SEM analysis is applied to examine the topography of the activated carbon, including surface analysis and the texture of the produced activated carbon. The results of the SEM analysis can be seen in Figure 4, which depicts the differences in topography and morphology of the kepok banana peel powder before and after activation using various concentrations of activating agents. Figure 3(a) shows the kepok banana peel before the activation process, with a magnification of 3000x. In this image, the surface of the banana peel appears denser, and the pores are still closed. This indicates the presence of organic matrices that remain abundant and have not completely decomposed during the carbonization process, as well as the possibility that impurities were not fully removed during carbonization, potentially affecting the adsorption.

Figures 4(b), 3(c), and 3(d) depict the surface morphology of banana peel after the activation process using HCl at different concentrations. Figure 3(b) shows banana peel activated with 0.15 M HCl, while figure 3(c) presents banana peel activated with 0.2 M HCl, and figure 4(d) illustrates banana peel activated with 0.25 M HCl. The SEM sample testing was conducted at a magnification of 3,000x, with visualizations of the pores in the activated carbon from the kepok banana peel before and after activation using HCl. The results show that the pores in the activated kepok banana peel sample became larger and more open. This is consistent with the research by Wardani *et al.* (2018), which explains that as the pore size of activated carbon increases after activation, the adsorption efficiency also increases. The comparison among the three samples activated with different HCl concentrations, as shown in figures 4(b), 4(c), and 4(d), demonstrates a tendency for an increase in pore size and number as the acid concentration increases. Kepok banana peel activated with 0.15 M HCl (Figure 4(b)) exhibits a more open pore structure and contains more cavities compared to kepok banana peel activated with 0.2 M HCl (Figure 4(c)) and 0.25 M HCl (Figure 4(d)).

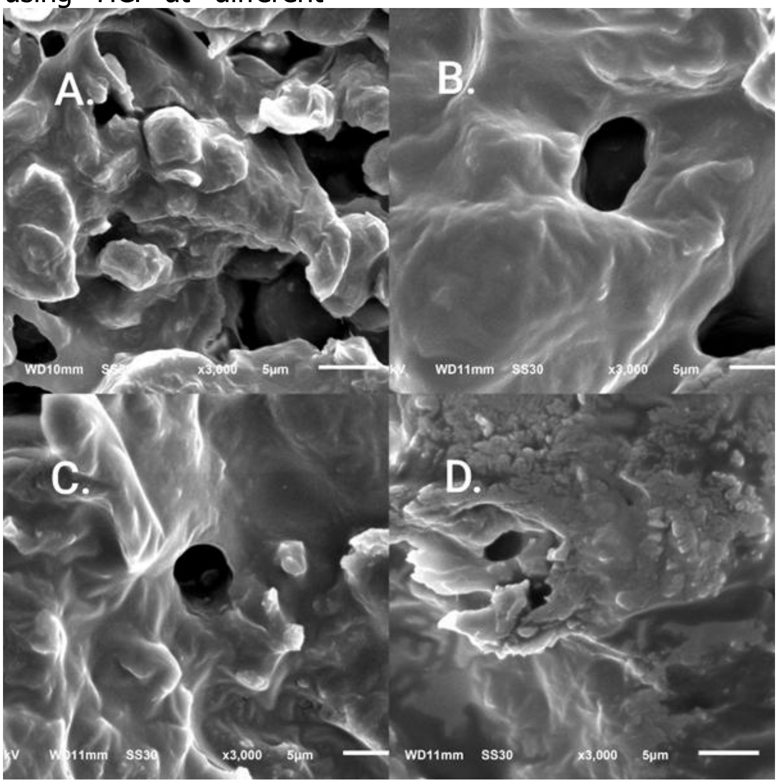


Figure 4. SEM images of Kepok banana peel powder before activation (a), after activation with 0.15 M HCl (b), after activation with 0,2 M HCl (c), and after activation with 0,25 M HCl (d)

The sample activated with 0.15 M HCl showed more uniform and evenly distributed pore formation compared to the samples activated with higher HCl concentrations. This suggests that overly high concentrations of HCl can lead to excessive dissolution of the carbon structure, ultimately reducing the material's specific surface area. Therefore, 0,15 M HCL is the recommended concentration for optimizing pore structure.

3.5. Characterization of Activated Carbon using FTIR

Based on the FTIR analysis results for the kepok banana peel adsorbent before activation (non-activated) and after activation (0.15M, 0.2M, and 0.25M), as shown in Figure 5, significant peaks were observed at 3481, 2927, 2856, 1736, 1458, 1374, and 885 cm^{-1} within the wavenumber range of 4000 to 500 cm^{-1}. The increase in HCl concentration enhances pore formation, expands surface area, and modifies functional groups, contributing to increased adsorption capacity. FTIR analysis shows differences in peak intensity and position, particularly in the O-H, C=O, and C-H groups, indicating structural changes due to acid treatment. The peaks at 3481 and 2927 cm^{-1} correspond to aliphatic C-H stretching, indicating the presence of compounds containing methyl or methylene groups. The strong peak at 1736 cm^{-1} indicates the presence of a carbonyl group (C=O), which typically appears in compounds such as esters, aldehydes, or ketones. The peak at 1458 cm^{-1} suggests the possible presence of C-H bending vibrations associated with aliphatic bonds. The peak at 1374 cm^{-1} may indicate the bending vibration of C-H in methyl groups. The lower peak at 885 cm^{-1} indicates the out-of-plane bending of aromatic C-H, confirming the presence of aromatic rings within the activated carbon matrix.

The presence of O-H and C-O bonds suggests that the activated carbon derived from kepok banana peel has more polar characteristics, which enhances its adsorption capability for dye molecules containing hydrophilic functional groups (Das & Kalyani, 2023). The high intensity peaks related to oxygenated functioal groups indicate the potential contribution of surface chemistry in adsorption mechanisms, particularly in hydrogen bonding and electrostatic interactions (Suhaimin *et al*., 2022).

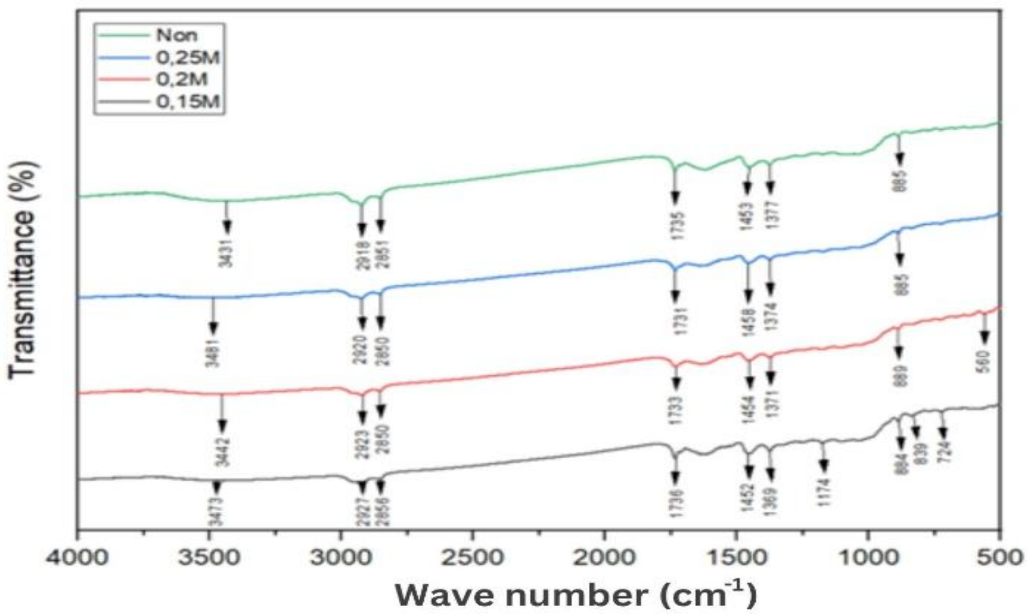


Figure 5. FTIR Test Results of Kepok Banana Peel

Studies have also shown that the presence of oxygen containing functional groups, such as hydroxyl and carboxyl groups, improves the adsorption of organic dyes due to increased surface polarity (Yang *et al*., 2021). Furthermore, the functional groups identified in the FTIR spectra indicate that the activated carbon underwent successful activation, as evidenced by the enhancement of oxygenated surface groups. The presence of a strong carbonyl peak at 1736 cm^{-1} is consistent with previous studies on biomass-derived activated carbon, which report the formation of carboxyl and lactone groups after chemical activation (Nazir *et al.*, 2023). These functional groups contribute to the adsorption efficiency by providing additional active sites for dye interaction. The adsorption of Indigosol Blue increases with higher HCl concentrations, with the highest efficiency at 0.25 M. This indicates that activation with 0.25 M HCl produces activated carbon with optimal adsorption properties, making it more effective in removing dye from aqueous solutions.

3.6. Adsorption Efficiency

Based on the graph, it can be observed that the adsorption efficiency of Indigosol Blue by kepok banana peel activated carbon treated with HCL at a concentration of 0,25M increases as the initial dye concentration increases. This indicates that at low initial concentrations, more active sites on the activated carbon are available to bind the dye. As the initial dye concentration increases, more dye molecules are bound to the activated carbon, resulting in higher adsorption efficiency. The highest adsorption efficiency reached 88.5% at an initial concentration of 30 ppm, indicating that activated carbon from kepok banana peel is effective in adsorbing Indigosol Blue dye, at low initial concentrations (Figure 6).

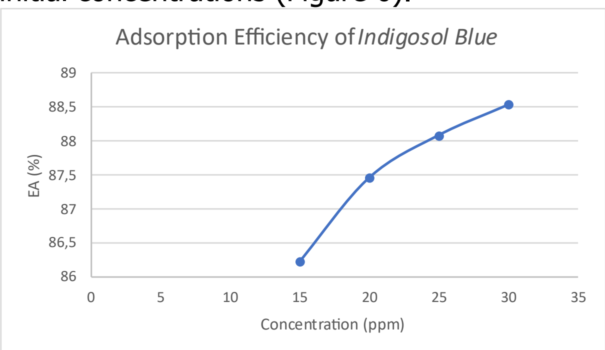


Figure 6. Adsorption Efficiency of Indigosol Blue Dye

The maximum adsorption capacity (qe max) is the highest qe value that can be achieved at a specific initial Indigosol Blue concentration. In the Figure 7, qe max is reached at an initial Indigosol Blue concentration of 35 ppm, with a qe max value of approximately 0.24 mg/g. The qe max value can be used to estimate the amount of activated carbon needed to adsorb Indigosol Blue from a solution with a specific initial concentration. The higher the qe max value, the less activated carbon is required to achieve the desired adsorption efficiency. Based on the above analysis, it can be concluded that kepok banana peel activated carbon treated with HCL at a concentration of 0,25M can be used effectively to adsorb Indigosol Blue. The adsorption capacity of Indigosol Blue by kepok banana peel activated carbon increases with increasing initial Indigosol Blue concentration. The qe max value in the figure is approximately 0.24 mg/g. The relationship between the initial Indigosol Blue concentration and the adsorption capacity of Indigosol Blue by kepok banana peel activated carbon can be modeled using the Langmuir equation (Figure 8).

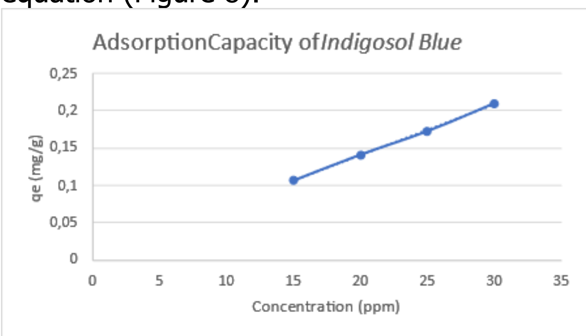


Figure 7. Adsorption Capacity of Indigosol Blue Dye

3.7. Adsorption Isotherms

Various concentrations of 15, 20, 25, and 30 ppm were prepared and applied at optimal contact time. In this step, activated carbon samples treated with HCL at 0,25M were used to evaluate their adsorption performance. An isotherm describes the equilibrium relationship between the adsorbate in the solid and liquid phases. Adsorption isotherm determination was carried out to study the adsorption mechanism between kepok banana peel activated carbon and Indigosol Blue adsorbate.

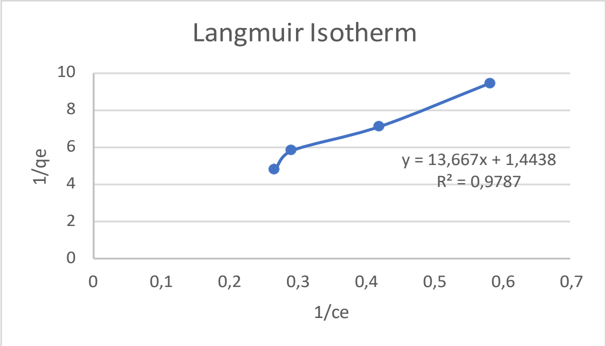


Figure 8. Langmuir Isotherm of Kepok Banana Peel Adsorbent

To assess the appropriate isotherm model, Langmuir and Freundlich isotherm models were applied to study the adsorption pattern of Indigosol Blue dye on the surface of activated carbon. The Langmuir isotherm equation is illustrated with a graph of Ce/qe versus Ce, while a graph of log qe vs. log Ce was created based on the Freundlich isotherm equation. From the analysis of both isotherms, a comparison between the Langmuir and Freundlich isotherms for kepok banana peel adsorbent was obtained, as shown in Figures 8 and 9.

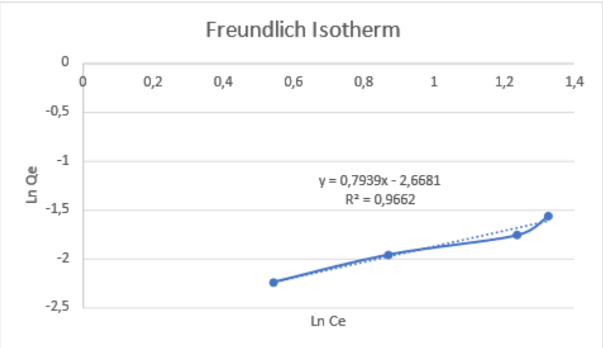


Figure 9. Freundlich Isotherm of Kepok Banana Peel Adsorbent

Figures 8 and 9 display curves representing the adsorption isotherms of kepok banana peel activated carbon for Indigosol Blue dye solution. The isotherm model that best fits the research data was analyzed using simple linear regression, considering the correlation coefficient (R^2) values to determine the contribution of the variables. Based on the linear regression coefficient (R^2) values from each graph, the Langmuir isotherm graph shows an R^2 value almost similar to the Freundlich isotherm graph, which are 0.97 and 0.96, respectively. This indicates that the adsorption of Indigosol Blue dye on the surface of activated carbon follows both isotherm patterns. However, it should be noted that the closer the R^2 value is to 1, the greater the influence between variables, indicating a better relationship. Referring to the data shown in the figures, the adsorption characteristics of kepok banana peel adsorbent appear to better match the Langmuir isotherm, as the correlation coefficient (R^2) obtained is higher and closer to 1 compared to the Freundlich isotherm. The different models assume different adsorption mechanisms.

The effectiveness of activated carbon derived from kepok banana peels in adsorbing Indigosol Blue dye is also reflected in its high adsorption capacity, reaching 88.5%. This reinforces the conclusion that adsorption occurs in a single layer (monolayer) and that the surface is homogeneous, as assumed by the Langmuir model. Each pore of the activated carbon can only absorb a single dye molecule, further strengthening the efficient adsorption characteristics. The linear equation of the Langmuir isotherm curve is used to identify Langmuir parameters, such as KL (Langmuir Equilibrium Constant), which serves as a key indicator in determining the efficiency of this adsorption process. Beyond its theoretical contributions, these findings also have significant practical implications for aquatic ecosystem restoration. Activated carbon from banana peels can be applied through floating adsorption units or integrated into biological filters in water channels and small rivers. These units are expected to treat up to 500 liters of water per day per unit and reduce dye concentrations by up to 90% after a single usage cycle. A study by Harimu *et al.* (2020) found that using this adsorbent in natural waters can increase.

4. Conclusion

This study aimed to evaluate the adsorption efficiency of activated carbon derived from Kepok banana peels in removing Indigosol Blue from wastewater. The findings demonstrate that activated carbon treated with 0.25M HCl can achieve an impressive adsorption efficiency of 88.5% at an initial dye concentration of 30 ppm. The optimal adsorption conditions were determined to be an adsorbent mass of 125 grams and a contact time of 120 minutes, ensuring maximum dye removal. These findings contribute to the development of sustainable, low-cost adsorbents for industrial wastewater treatment, particularly in reducing aquatic environmental pollution. By utilizing agricultural waste as a viable adsorbent, this research aligns with broader efforts to enhance eco-friendly wastewater treatment technologies.

Additionally, this study builds upon previous research by demonstrating the potential of banana peel-derived activated carbon in continuous adsorption systems. The column adsorption method exhibited a maximum adsorption capacity (qe max) of 0.24 mg/g, suggesting its effectiveness in treating wastewater containing Indigosol Blue. Despite its promising results, this study acknowledges certain limitations. Factors such as adsorbent regeneration and long-term performance require further investigation. Future research should explore modifications to the adsorbent surface properties and conduct pilot-scale studies to assess its feasibility and scalability for industrial applications. In conclusion, this study highlights the potential of Kepok banana peel-derived activated carbon as an efficient and sustainable adsorbent for dye removal. Further advancements in adsorption techniques and process optimization could enhance its applicability in real-world wastewater treatment scenarios.

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Conflict of interests

The authors declare that there are no conflicts of interest related to this study. All research activities were conducted with integrity and transparency, ensuring that personal or financial relationships did not influence the results or interpretation of the data. Any potential conflicts have been addressed, and the authors affirm their commitment to ethical research practices.

Data availability statement

To enhance the scientific credibility of this study, all data generated or analyzed during this research are available upon reasonable request from the corresponding author. The datasets include all relevant experimental results, methodology details, and supplementary information. There are no sensitive data involved in this project, ensuring full transparency and accessibility for further research.

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