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Potential of Jackfruit Wood as Activated Carbon for Adsorption of Heavy Metal Mercury (Hg) through Pyrolysis Method

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Abstract: *Water pollution caused by heavy metal mercury is a serious problem today. This study aims to utilize jackfruit wood waste as a natural adsorbent to overcome the problem of water pollution due to heavy metal mercury. The methods in this research include jackfruit wood preparation, hydrochar synthesis through pyrolysis, hydrochar activation, wastewater preparation, batch adsorbent optimum conditions, and dynamic adsorption process (Fixed-Bed Column). This study aims to synthesize and test jackfruit wood-activated carbon adsorbing mercury from liquid waste. Synthesis was carried out through pyrolysis of jackfruit wood waste and activation using HCl. Adsorption tests were carried out with variations in pH, contact time, acid concentration, and mercury concentration, then evaluated using the Langmuir and Freundlich isotherm models and adsorption kinetics. The results showed that the best activation occurred at 0.4 M HCl, with an optimal pH of 3, which resulted in an adsorption efficiency of 85.53% and a capacity of 34 mg/g. The optimal contact time was achieved at 80 minutes with an adsorption of 83.28%. The kinetics followed the second-order model, and the adsorption capacity reached a maximum of 130 mg at a concentration of 500 ppm. The adsorption process followed the Langmuir model, showing the formation of a monolayer with an adsorption capacity of 67.52 mg/g for mercury. The calculation results show that 32.04 kJ/mol of energy is needed for mercury adsorption by jackfruit wood.*

Keywords*: Acid Activation, Jackfruit Wood, Mercury, Pyrolysis*

INTRODUCTION

One of the efforts to change the situation towards a more advanced direction is industrial development. Human life can not only be improved by development, but development can also sacrifice many things, especially the surrounding environment. Various industrial and development activities reduce environmental quality, especially in the aquatic environment (Pereiz, Nafisah, et al., 2023). Abiotic ecosystem factors can be affected by substances that enter the water. These include changes in community structure, the death of organisms that are not resistant to chemicals, and changes in water quality (Ekaputra Bernadus et al., 2021).

One of the aquatic habitats that is most vulnerable to pollution is the river ecosystem. This is caused by the flow of rainwater that carries pollutants from land to rivers (Nafisah et al., 2023). Heavy metal pollution is one of the most common types of environmental pollution found in river water. Heavy metals can harm people who use water and live things in the river. The heavy metals found come from industrial wastewater that is usually not treated first, which causes frequent river pollution (Afifudin et al., 2024). Heavy metals are transition elements with an atomic density greater than 6 g/cm^3 (Afifudin et al., 2024)(Kamarati et al., 2018). Heavy metals released from industrial production contain one or more toxins, sometimes more than the permitted limit (Yudo, 2018). Industrial waste contains toxic compounds containing heavy metals such as mercury (Hg), lead (Pb), cadmium (Cd), chromium (Cr), and zinc (Zn) (Rahmadewi et al., 2019).

Mercury is considered the most dangerous pollutant of all types of heavy metals. However, it turns out that its production is quite large and widely used. Pollution caused by heavy metals is a significant problem (Widianti et al., 2024). At room temperature, mercury is a liquid trace element. This metal also has a high specific gravity and high electrical conductivity. Due to its properties, mercury is widely used in industrial and laboratory activities. This metal liquid is silvery white with a specific gravity of 13.55 g/cm3 and an atomic weight of 200.6. Its boiling point is 356.90 degrees Celsius, and its freezing point is 38.87 degrees celsius (Widianti et al., 2024).

Various methods have been used to remove heavy metals from water, including chemical precipitation, flocculation or coagulation, ion exchange, reverse osmosis, electrochemical operations, the use of microorganisms, and adsorption (Lingkungan et al., 2025)(Pereiz et al., 2025). Adsorption is the most straightforward of all these methods. Using natural adsorbents during adsorption is another way to treat mercury waste. Therefore, the operational costs of processing are expected to be cheaper (Irawan et al., 2014).

The jackfruit tree (Artocarpus heterophyllus) is a tropical fruit plant with many benefits. This tree originates from South India and can be planted in areas less than 1,000 meters above sea level (Rizkyka & Riyanti, 2024). The jackfruit tree (Artocarphus heterophyllus) is one of Indonesia's most common tropical fruit trees. Jackfruit trees can bear fruit all year round from the age of five to ten years. Jackfruit trees can reach a productive age of 20-30 years with a maximum height of 10-15 m. Jackfruit trees are usually cut down after their productive period; the wood is used to make furniture and crafts (Segah et al., 2024)(Rini et al., 2019). In addition, jackfruit wood can also be used as a raw material for activated carbon. According to research conducted by Mutiara (Mutiara et al., 2018), jackfruit sawdust, which is pyrolyzed into activated carbon, can be an adsorbent in processing heavy metal waste. Jackfruit wood contains pentosan, lignin, and cellulose. The cellulose content of jackfruit wood can be used to make activated carbon. Based on research conducted by Sa'diyah (Sa'diyah et al., 2021), sawdust waste has great potential to be processed into activated carbon because it contains cellulose and lignin, which cause sawdust to be able to bind heavy metal ions (Pereiz, Pebriyanto, et al., 2023) (Pereiz et al., 2024).

In recent times, efforts to control heavy metal waste have been growing, which has encouraged the search for new methods that are cheap, efficient, and effective. One of them is using activated carbon to absorb metal ions. Activated carbon is a type of carbon that has a vast surface area. Activated carbon is also called activated charcoal (Prabarini & Okayadnya, 2014). Activated carbon consists of 90-99% carbon and contains elements from various other materials, such as hydrogen, oxygen, sulfur, and nitrogen (Palallo & Oskar, 2023). One gram of activated carbon can produce material with a surface area of about 500 m^2. In addition to increasing its surface area, activation is also helpful in increasing the adsorption capacity of activated carbon to absorb many impurities in water. The surface area of activated carbon is usually 400-1400 m^2/gram (Prabarini & Okayadnya, 2014). The large surface area of activated carbon is produced by pyrolysis and physical or chemical activation processes (Ayuchecaria et al., 2024) (Pereiz, Chuchita, et al., 2023).

One way to reduce the cost of activated carbon production is carbonation through the pyrolysis process and acid activation. Pyrolysis is a heating process without outside air or oxygen. During the heating process, an inert gas is introduced into the reactor to ensure that the process does not involve air or oxygen. The compound will decompose into carbon during pyrolysis at temperatures between 200–300°C. During this process, activation causes physical changes to the carbon surface (removal of hydrocarbons). Furthermore, chemical activation is needed to increase the adsorption capacity of activated carbon (Sa'diyah et al., 2021). The chemical activators used are HCl and NaOH. Acid functions to modify the structure and increase the surface area, while the base functions as a neutralizing agent (Ratna Kumalasari et al., 2023) (Pereiz, 2024).

Research on the potential of jackfruit wood for removing heavy metals, including those conducted by Mutiara, showed the potential of jackfruit sawdust as an effective adsorbent for absorbing various types of heavy metals. In addition, the research also showed that jackfruit sawdust that had been modified with phosphoric acid had good potential as a natural material for cleaning water from heavy metal contamination, in this case, Hg(II). Based on this, this study aims to more specifically investigate the potential of jackfruit wood as activated carbon in adsorbing the heavy metal mercury (Hg)(Mutiara et al., 2018).

RESEARCH METHODS

Materials and Tools

The materials used in this study consisted of liquid waste from the upper reaches of the Kahayan River in Palangka Raya City, Central Kalimantan Province, jackfruit wood, HCl p.a, NaOH p.a, H_3PO_4 p.a, $HgCl_2$, glass wool, filter paper, ice cubes, and demineralized water. The tools used in this study consisted of an analytical balance, magnetic stirrer, pyrolysis reactor, condenser, hose, pipe, blender, stopwatch, burette or box-shaped glass, clamps and static, water pump, knife, 100 mesh sieve, pH meter, aluminum foil, glassware, and Atomic Absorption Spectrometry (AAS) instruments.

Methods

Preparation of Jackfruit Wood

Jackfruit wood was obtained from wood processing waste at CV. Banggaris Sejahtera is located in Palangka Raya, Central Kalimantan Province. Jackfruit wood was washed several times and dried for one day (24 hours) in an oven at a temperature of 105°C. After that, the sample size was reduced with a blender and sieved.

Hydrochar Synthesis through Pyrolysis

The hydrochar synthesis process was carried out using a pyrolysis reactor; as much as 8 grams of jackfruit wood waste sample was added with 70 mL of deionized water and adjusted so the mixture had a pH of 1 with H_3PO_4. Then, it is put into a pyrolysis reactor at a temperature of 260°C for 6 hours. Furthermore, the liquid phase and the solid phase (residue) were separated using vacuum filtration. The solid phase (residue) produced from this process is called hydrochar. Hydrochar was dried at 105°C for 2-3 hours using an oven.

Hydrochar Activation (Activated Carbon Making)

The activator used for hydrochar activation is HCl. The ratio between hydrochar and activator is 1:10 (w/v). Hydrochar is ground, weighed as much as 10 grams, and soaked for 24 hours in 100 mL of HCl solution with variations of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8

M. After that, the sample is filtered and washed to ensure its pH is neutral. The resulting residue is then dried at a temperature of 110°C for 3 hours using an oven.

Determination of Liquid Waste Preparation

The liquid waste used as a test sample was taken from the Kahayan River in Palangka Raya City, Central Kalimantan Province. The water sampling method used is grab sampling. The wastewater sample is filtered to remove dirt or analytes in the sampling process. Before adsorption is carried out, the liquid waste sample is analyzed to determine the concentration of Hg (II) using AAS and the degree of acidity (pH).

Optimum Adsorbent Conditions in Batch

The optimum conditions for the adsorption process will be carried out in batches with three parameters. The standard analyte can determine the effect of the matrix on the liquid waste sample, and the spike technique was used. $HgCl_2$ solution as a source of Hg(II) will be added to the liquid waste. The optimum pH is determined by adding 1 gram of adsorbent to 100 mL of liquid waste with pH variations. The pH variations of the liquid waste used are 1, 2, 3, 4, 5, 6, 7, and 8. The pH variations of the liquid waste are mixed using NaOH and HCl with a concentration of 0.1 M. The mixture is stirred using a shaker for 60 minutes at 150 rpm. Then, the mixture is left for 15 minutes and then filtered. The filtrate is tested using AAS, and the absorption efficiency (%) is calculated. (Oksal et al., 2025).

The optimum time is determined by adding a gram of adsorbent to 100 mL of liquid waste using the optimum pH. Using a shaker at a speed of 150 rpm, the mixture was stirred with contact time variations of 20, 40, 60, 80, 100, and 120 minutes. The mixture was left for 15 minutes before being filtered. The filtrate was tested with AAS, and then the adsorption efficiency (%) and adsorption kinetics were calculated. The variation of the adsorbent mass was used to determine the adsorption isotherm. The mass variations used were 1, 1.5, 2, 2.5 and 3 grams. The adsorbent was added to 100 mL of liquid waste using the optimum pH and time. Furthermore, the mixture was left for 15 minutes and then filtered. The filtrate was tested with AAS, then the adsorption efficiency (%), adsorption capacity, and adsorption isotherm were calculated.

RESULTS AND DISCUSSION

This study began with the preparation of jackfruit wood. Jackfruit wood waste was cleaned and dried using an oven and then reduced in size using a blender. The dried jackfruit wood powder was then burned. This burning was carried out by pyrolysis. Pyrolysis is a heating process without outside air or oxygen. During the heating process, an inert gas is introduced into the reactor to ensure that the process does not involve air or oxygen. The compound will decompose into carbon during pyrolysis at 200–300°C (Sa'diyah et al., 2021). The solid phase (residue) produced from the pyrolysis process is called hydrochar (Figure 1). Acid activation is needed to increase the adsorption capacity of activated carbon.

Activated carbon is charcoal that has changed physical and chemical properties due to activation treatment with chemical activators or heating at high temperatures. Activated carbon will form an amorphous solution that consists mainly of free carbon. This amorphous has a hollow inner surface, is black, odorless, tasteless, and has a greater capacity to absorb than carbon that has not been activated (Figure 2). Activated carbon is used as an adsorbent in various processes, such as waste treatment and water purification (Sa'diyah et al., 2021).

Figure 1. Hydrochar

Activation means changing carbon with a low absorption capacity into carbon with a high absorption capacity. This can be achieved in several ways, such as using hot steam, carbon dioxide gas at temperatures between 700–1100°C, or adding mineral materials as activators. Activation also functions to remove tar attached to the pores and carbon surfaces. Activation increases the inner surface area, produces a large volume of tiny capillaries, and changes the inner surface of the pore structure. The chemical activators used in this study were HCl and NaOH. Acid functions to modify the structure and increase the surface area, while the base functions as a neutralizing agent (Sa'diyah et al., 2021). Factors that influence the activation process are particle size, activation time, activation temperature, activator ratio and type of activator (Darajat et al., 2023).

Figure 2. Activated Carbon

Acid Concentration Variation

The purpose of the variation of HCl concentration is to determine the optimal concentration of hydrochloric acid (HCl) in activating activated carbon from jackfruit wood so that the maximum mercury (Hg) adsorption capacity is obtained. Based on the results of this study, it is known that the most optimal HCl concentration is 0.4 M. When the HCl concentration is increased to more than 0.4 M, the adsorbent is in a stable condition or reaches saturation point (Figure 3). This is because mercury (Hg) no longer has a place to bond with the adsorbent. In other words, the mercury compound no longer has a group on the adsorbent to bond with.

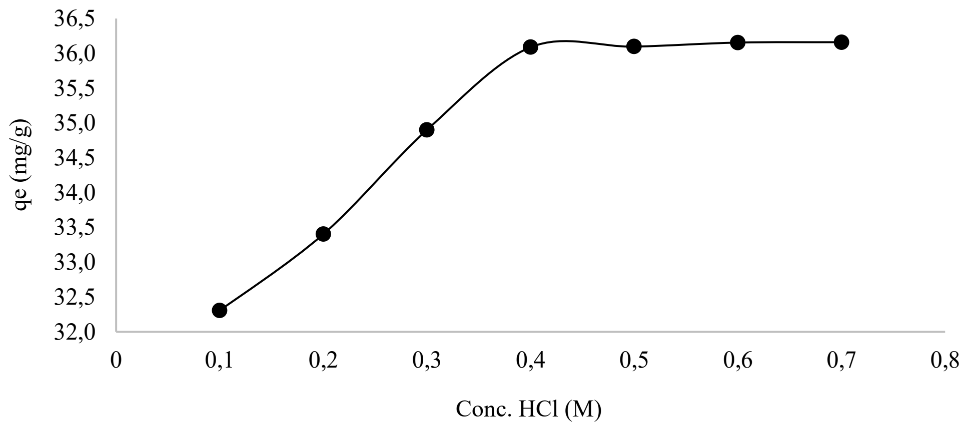

Figure 3. Effect of HCl Concentration on the Adsorption Capacity of Jackfruit Wood

pH Variation

The effect of pH on activated carbon from jackfruit wood can be seen in Figure 4. The adsorption capacity of jackfruit wood is good at a relatively low pH. The optimum pH value for the adsorption process is 3. This shows that adsorption will run optimally when the solution has a relatively acidic pH. The study results showed that the adsorption process by jackfruit wood began to occur significantly at pH 1-7. The optimal pH for activated carbon from jackfruit wood to adsorb mercury is 3. This is because the adsorbent has a positive charge. So, it will be easier to adsorb mercury in acidic conditions. In acidic conditions, the solution will be filled with protons (H^+), increasing the mercury adsorption process, while mercury has a negative charge.

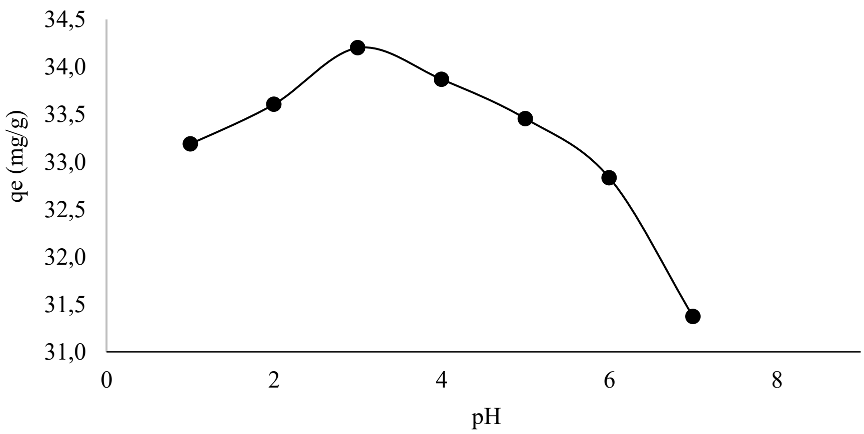

Figure 4. Effect of pH on the Adsorption Capacity of Jackfruit Wood

Contact Time Variation

Figure 5 shows the effect of contact time on the adsorption capacity of jackfruit wood adsorbent on mercury. Low contact times (below 20 minutes) will result in a low adsorption process. This is because not all mercury is adsorbed into the adsorbent. At high contact times (above 80 minutes), the adsorption process will be stable and even relatively decrease. The mercury previously adsorbed in the adsorbent can then be free and dissolved into the solution.

Based on research data, mercury adsorption on activated carbon from jackfruit wood shows that the ideal contact time is 80 minutes.

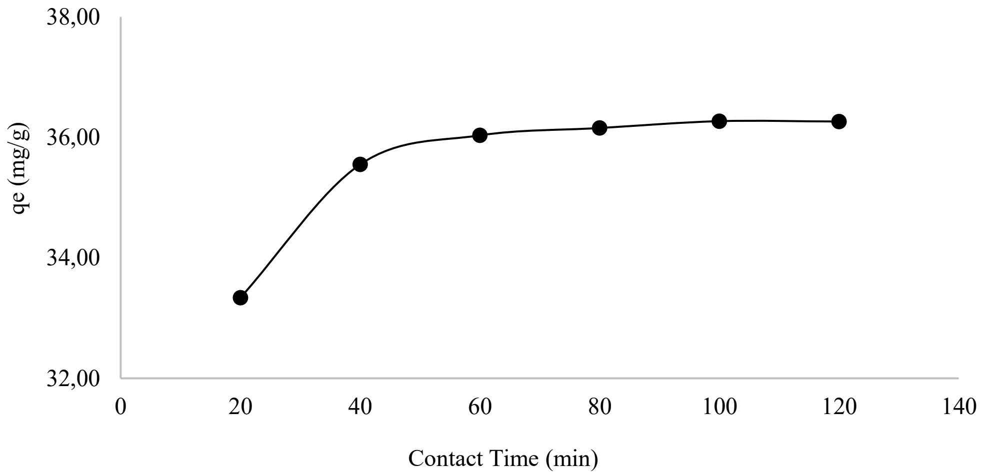

Figure 5. Effect of Contact Time on Jackfruit Wood Adsorption Capacity

Reaction Order

Pseudo-first-order and second-order kinetic equations were used to regress the data (Figure 6 and 7). These graphs were used to calculate the correlation coefficient (R^2), which measures how applicable each model is. The linearity of these plots indicates that both models are applicable. The Pseudo second-order model fits the experimental data better than the Pseudo first-order model, based on the findings of the correlation coefficients ($R^2 > 0.9899$; $R^2 > 0.999$).

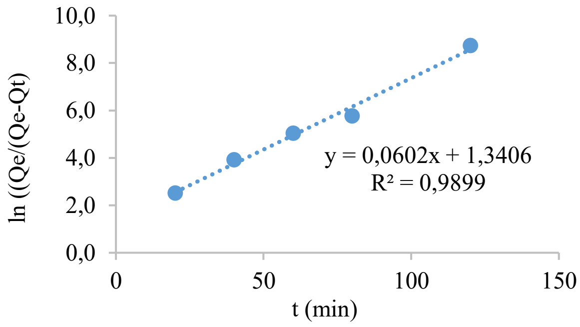

Figure 6. Pseudo First Order

In addition to the adsorption mechanism, chemisorption was also demonstrated by the adsorption kinetic model, which showed that the square of the mercury concentration determines the adsorption rate, represented by $(q_e - q_t)^2$. Table 1 displays the resulting values of the kinetic parameters.

Table 1. Adsorption Kinetic Model

Material	Pseudo first order		Pseudo second order	
	β (minute^{-1})	**R^2**	**k_2 (g/mg.minute)**	**R^2**
Actived carbon	0.0204	0.9899	0.01712	0.9998

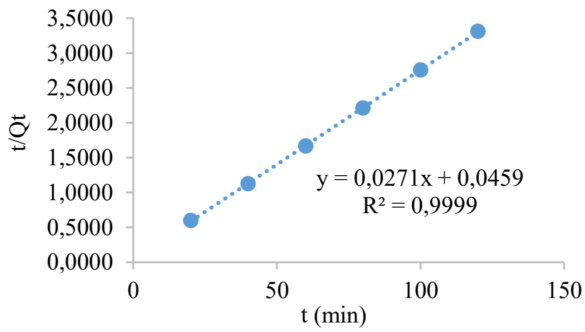

Figure 7. Pseudo Second Order

Concentration Variation

Figure 7 illustrates how mercury concentration changes affect jackfruit wood's adsorption capacity. A low adsorption process will also occur at low mercury concentrations (below 500 ppm). This is because much adsorbent remains in the solution while the mercury has been wholly absorbed into the adsorbent. A stable adsorption process will occur at high mercury concentrations (above 500 ppm). All adsorbents have reached their maximum adsorption capacity, and no adsorbent has been dissolved in the solution. Research shows that mercury adsorption on activated carbon from jackfruit wood reaches its peak capacity at around 500 ppm, then tends to approach equilibrium before decreasing as the concentration increases.

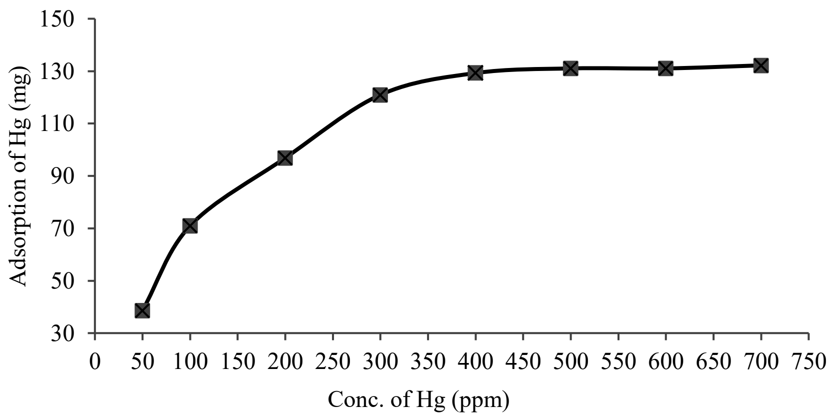

Figure 7. Effect of Mercury (Hg) Concentration on Jackfruit Wood Adsorption

Adsorption Isotherm

Adsorption energy, capacity, and adsorption equilibrium are all determined by the adsorption equilibrium. How much material is adsorbed and the concentration of the substance at equilibrium by the adsorbent is described through the isotherm pattern. In addition to helping determine the correlation between mercury adsorption isotherms and experimental data, two-parameter isotherm models (Langmuir and Freundlich) were also used to evaluate the data. The results are shown in Figures 8 and 9.

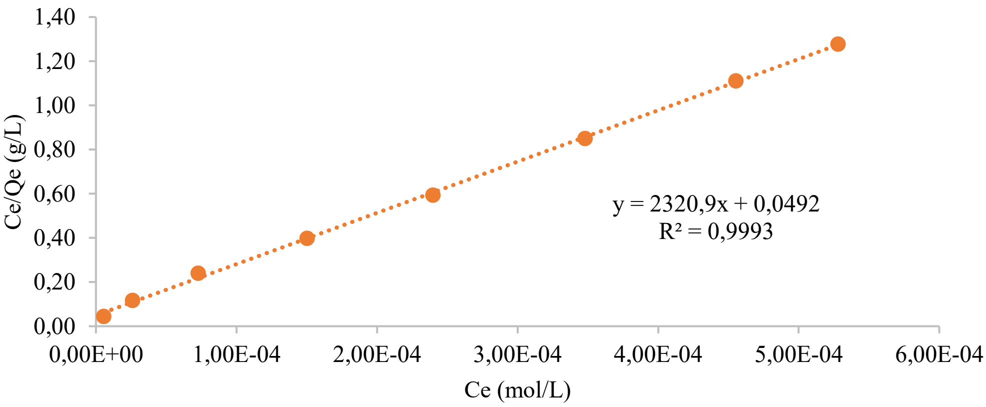

Figure 8. Langmuir Adsorption Isotherm Model Curve

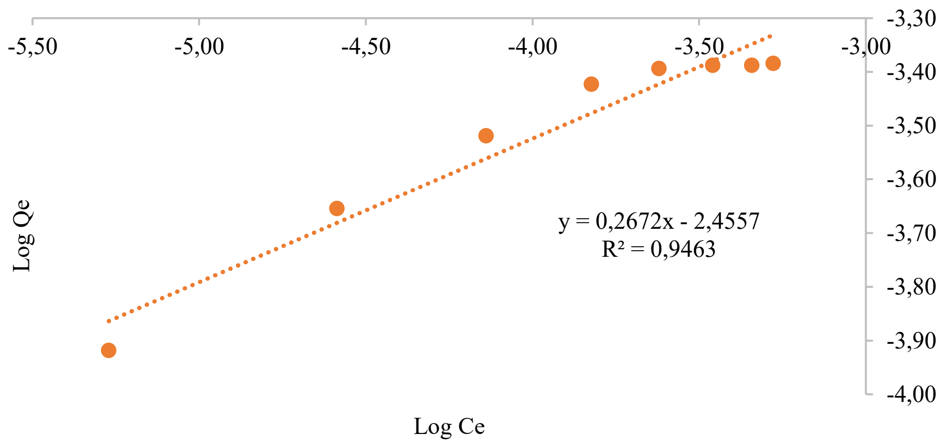

Figure 9. Freundlich Adsorption Isotherm Model Curve

This graph (Figures 8 and 9) was used to calculate the correlation coefficient (R^2), which measures how applicable each model is. The linearity of these plots indicates that the models are applicable. Based on the comparison of R^2 values, it can be concluded that the adsorption equation follows the Langmuir isotherm model because the Langmuir equation has an R^2 value of 0.9992, which is closer to 1. According to this hypothesis, chemisorption or strong electrostatic interactions are responsible for mercury adsorption on the adsorbent surface. Table 2 displays the results of the equilibrium parameters for the two isotherm models.

Table 2. Mercury Equilibrium Kinetic Model

Material	**Isotherm Langmuir**				**Isotherm Freundlich**		
Activated	**B (mg/g)**	**K (L/mol)**	**E (KJ/mol)**	**R^2**	**B (mg/g)**	**N**	**R^2**
carbon	67.52	48558.39	32.04	0.9993	3.574×10^{-3}	3.743	0.9463

The mercury adsorption capacity (B) on jackfruit wood material can be calculated using the Langmuir isotherm model, as shown in Table 2. Jackfruit wood's adsorption capacity (B) is 67.52 mg/g for mercury. The adsorption energy can be found using the Langmuir isotherm model and the formula E = RT ln K. The calculation results show that

32.04 kJ/mol of energy is needed for mercury adsorption by jackfruit wood. This indicates that electrostatic interactions between the two adsorbents and mercury occur.

CONCLUSIONS

This study aims to synthesize and test jackfruit wood-activated carbon adsorbing mercury from liquid waste. Synthesis was carried out through pyrolysis of jackfruit wood waste and activation using HCl. Adsorption tests were carried out with variations in pH, contact time, acid concentration, and mercury concentration, then evaluated using the Langmuir and Freundlich isotherm models and adsorption kinetics. The results showed that the best activation occurred at 0.4 M HCl, with an optimal pH of 3, which resulted in an adsorption efficiency of 85.53% and a capacity of 34 mg/g. The optimal contact time was achieved at 80 minutes with an adsorption of 83.28%. The kinetics followed the second-order model, and the adsorption capacity reached a maximum of 130 mg at a concentration of 500 ppm. The adsorption process followed the Langmuir model, showing the formation of a monolayer with an adsorption capacity of 67.52 mg/g for mercury. The calculation results show that 32.04 kJ/mol of energy is needed for mercury adsorption by jackfruit wood.

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