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Kinetics and Isotherm Studies of Cadmium (Cd) Adsorption Using Durian Peel (*Durio zibethinus*) Biomass

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Abstract**—***Cadmium (Cd) in wastewater from the industrial sector is a big cause of heavy metal pollution in water, thus it needs to be c leaned up correctly. Adsorption is a fairly inexpensive method for removing Cd from water, and the type of adsorbent used will depen d on how simple it is to procure and how it needs to be treated Durian peel (Durio zibethinus), comprising 50–60% cellulose, 5% lignin, essential oils, flavonoids, saponins, and carbon, may serve as a bioadsorbent due to its capacity to bind metal ions. This study aims to investigate th e adsorption kinetics and isotherm properties of cadmium (Cd) using durian peel biomass. It utilized durian peel waste from Central Sulawesi and q uantified the concentration of Cd ions by atomic absorption spectrophotometry (AAS). The findings indicate that Cd adsorption adheres to a second-order kinetic model, characterized by an average rate constant of 0.00007998 ppm^{-1} min^{-1}. At 80 minutes, the greatest adsorption r ate is 0.49 ppm min^{-1}, and the half-life is 125 minutes.*

Keywords**—***Cadmium adsorption, Durian peel, Bioadsorbent, Adsorption kinetics.*

I. INTRODUCTION

Water is one of the most plentiful natural resources on Earth, and it is necessary for both ecosystems and human life. However, its usability depends on following strict physical, chemical, and microbiological standards to make sure it is safe for eating, farming, and industrial use [1], [2]. The swift growth of industrial activities in recent times has resulted in a dual-edged effect, producing significant economic benefits while also causing serious harm to the environment. The textile industry in Indonesia is a good example of this paradox. It brings in about 12.72% of the country's non-oil and gas exports [3], [4]. Even though these benefits exist, the industry's resource-hungry processes, which use a lot of water, synthetic dyes, and dangerous organic compounds, are very bad for aquatic environments and make pollution and eutrophication worse in receiving water bodies [5]. Adding to these problems, the increasing use of heavy metals in different industrial processes has made contamination worse in both freshwater and marine systems, causing bioaccumulation, toxicity, and long-term damage to ecosystems [6], [7]. It is essential to address these anthropogenic pressures to reduce risks to water quality and encourage sustainable development.

Cadmium (Cd) is one of the most harmful heavy metals since it stays in the environment for a long time and builds up in living things. Cd is a byproduct of zinc refining that is released unintentionally. For every metric ton of zinc treated, about 3 kg of Cd is released [8]. It is widely used in battery manufacture, electroplating, and metal smelting. This broad use in industry has led to higher levels of Cd in effluents that are released into water systems, where it is very soluble and mobile, making it easy for it to spread through water cycles. Cadmium (Cd) is quite hazardous, even at levels considerably below 0.005 mg/L, which is what the World Health Organization says is safe. It is the second most dangerous substance for the environment and human health after mercury [9]. Chronic exposure to Cd has been definitively associated with significant physiological impairments, including pulmonary and renal dysfunction, hepatic damage, hypertension, and gastrointestinal disturbances, highlighting its carcinogenic and mutagenic potential [10], [11]. Consequently, the necessity for novel and effective remediation technologies, including adsorption, precipitation, and enhanced oxidation processes, is paramount to mitigate Cd penetration into aquatic systems and preserve ecological integrity and public health [7].

Several physical and chemical treatment methods have been developed, including precipitation, coagulation, and ion exchange. However, these methods remain costly, particularly in developing countries [12]–[14]. Adsorption has emerged as an attractive alternative, being both efficient and relatively economical for wastewater treatment. The choice of adsorbent material is critical, with processing costs, availability, and adsorption efficiency being key considerations. Conventional adsorbents are often expensive, prompting interest in low-cost and sustainable options derived from biomass waste [15]–[17].

Durian (*Durio zibethinus*), a tropical fruit extensively cultivated in regions such as Central Sulawesi, Indonesia, is primarily valued for its creamy, edible pulp, which accounts for merely 20.52% of the total fruit weight [18]. The substantial remainder approximately 79.48% comprises inedible components, predominantly the thick rind (peel) and seeds, which are routinely discarded as agricultural waste [19]. Inadequate management of this waste, particularly through open dumping or incineration, poses significant environmental risks, including the emission of malodorous volatile compounds and the release of particulate matter and greenhouse gases that contribute to air and soil pollution [19].

From a chemical perspective, durian peel is rich in lignocellulosic materials, containing 50–60% cellulose, 5% lignin, and 5% starch, alongside bioactive constituents such as essential oils, flavonoids, saponins, and polyphenolic compounds [18]. The abundance of hydroxyl (-OH) and carboxyl (-COOH) functional groups inherent in its cellulose matrix endows durian peel with exceptional chelating capabilities, enabling efficient adsorption of heavy metal ions, including cadmium (Cd), from contaminated aqueous solutions [5], [18]. This positions durian peel as a cost-effective and sustainable bioadsorbent for wastewater remediation, particularly in addressing anthropogenic metal pollution prevalent in industrial effluents. Moreover, valorising such agro-industrial byproducts into functional adsorbents not only alleviates the ecological footprint associated with waste accumulation but also fosters circular economy principles by generating economic value through resource recovery and reducing reliance on synthetic alternatives [18].

Durian (*Durio zibethinus*) is a tropical fruit that is grown a lot in places like Central Sulawesi, Indonesia. Most people like it for its creamy, edible pulp, which makes up only 20.52% of the total fruit weight [18]. The large part that is left over, about 79.48%, is made up of parts that can't be eaten, mostly the thick rind (peel) and seeds, which are usually thrown away as agricultural waste [19]. Poor handling of this waste, especially through open dumping or burning, is bad for the environment because it releases smelly volatile compounds and particulate matter and greenhouse gases that pollute the air and soil (Kusumaningtyas & Syah, 2020). From a chemical point of view, durian peel is full of lignocellulosic materials. It has 50–60% cellulose, 5% lignin, and 5% starch, as well as bioactive compounds like essential oils, flavonoids, saponins, and polyphenolic compounds [18]. The cellulose matrix in durian peel has a lot of hydroxyls (-OH) and carboxyl (-COOH) functional groups. This gives it great chelating abilities, which means it can easily absorb heavy metal ions like cadmium (Cd) from contaminated water [5], [18]. This makes durian peel a cheap and long-lasting bioadsorbent for cleaning up wastewater, especially when it comes to getting rid of metals that come from human activities and are common in industrial effluents. Furthermore, transforming agro-industrial byproducts into functional adsorbents mitigates the ecological impact of waste accumulation and promotes circular economy principles by creating economic value through resource recovery and decreasing dependence on synthetic alternatives [18].

In our prior research, we examined the adsorption process, which may be further delineated using equilibrium isotherm models, including the Langmuir and Freundlich isotherms [18]. These models elucidate the adsorption equilibrium by characterizing the distribution of the adsorbate between the liquid phase and the adsorbent surface at different equilibrium concentrations. The Langmuir isotherm posits monolayer adsorption on a homogeneous surface characterized by fixed adsorption sites and the absence of lateral interactions among adsorbed molecules. In contrast, the Freundlich isotherm considers multilayer adsorption on heterogeneous surfaces, frequently displaying favourable or unfavourable isotherms contingent upon the heterogeneity factor. Moreover, the kinetics of adsorption can be clarified using pseudo-order models, such as pseudo-zero-order, pseudo-first-order, pseudo-second order, and higher-order variations. These kinetic models assist identify the rate-controlling phases and the mechanisms behind them, like physisorption or chemisorption. This makes it easier to find the best process parameters for real-world uses like treating wastewater and getting rid of pollutants.

This study seeks to clarify the adsorption behaviour of cadmium (Cd^{2+}) ions by utilizing durian peel biomass as a sustainable, cost-effective adsorbent sourced from agricultural waste. The main goals are to look at the adsorption kinetics and equilibrium isotherm features. This will help us understand how heavy metal remediation works and how to make it work better. Experimental investigations were executed under diverse operational parameters, encompassing adsorbent dose (0.5–5.0 g/L), contact time (5–120 min), solution pH (2–8), and initial Cd^{2+} concentration (10–100 mg/L), to evaluate their impact on adsorption efficiency and capacity.

II. Methods

A. Materials and Equipments

The study included common laboratory equipment such a 100-mL Erlenmeyer flask, a 25-mL graduated cylinder, a 1000-mL volumetric flask, a 100-mL beaker, a dropper pipette, a funnel, a spatula, and a stirring rod. Some of the tools that helped were an oven, a desiccator, a digital balance, a blender, a shaker, a spray bottle, a stopwatch, and a 200-mesh sieve. Whatman filter paper was used for filtration, and an atomic absorption spectrophotometer (AAS) was used to quantify absorbance. The materials used were durian peel biomass, cadmium sulphate monohydrate ($CdSO_4 \cdot H_2O$), distilled water, aluminium foil, labelling paper, and tissue.

B. Experimental Procedure

1. Preparation of Durian Peel Biomass
   Durian peels sourced from Bondoyong village, Parigi Moutong district (Central Sulawesi), were separated from the pulp, thoroughly washed, cut into small pieces, dried, ground, and sieved through a 200-mesh sieve to produce a uniform adsorbent.
2. Preparation of Cadmium Solutions
   a. 1000 ppm Stock Solution: 2.017 g of $CdSO_4 \cdot H_2O$ was dissolved in distilled water, transferred into a 1000-mL volumetric flask, and diluted to the mark.
   b. 100 ppm Working Solution: 10 mL of the 1000 ppm stock was diluted to 100 mL with distilled water.
3. Characterization of Biomass
   Based on Indonesian National Standard (SNI 06-3730-1995), the adsorbent quality was determined by:
   a. Moisture Content: Calculated by drying the biomass to constant weight.
   b. Ash Content: Determined by ignition at high temperature to constant mass.
4. Optimization of Adsorption Parameters

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a. Adsorbent Weight: Biomass (1.0–3.0 g) was added to 50 mL of 100 ppm Cd solution at pH 5, shaken for 60 minutes, left to stand, filtered, and analysed by AAS at 324.8 nm.
b. Contact Time: Using the optimum biomass weight, adsorption was tested at 20, 40, 60, 80, and 100 minutes.
c. pH Variation: Adsorption was evaluated at different pH levels while maintaining the optimum dose and time.
d. Concentration Variation: Cd solutions with concentrations of 20–180 ppm were treated with the optimum biomass dose at optimum pH and contact time.

C. Data Analysis

1. Adsorption Capacity
   Adsorbed cadmium was calculated as:
   $$Cb = Ci - Cq \quad (1)$$
   Cb = Absorbed cadmium concentration (mg/L)
   Ci = Initial concentration of cadmium solution (mg/l)
   Ceq= Concentration of unabsorbed cadmium solution (mg/L)
   $$\%\,Cd = \frac{Cb}{Ci} \times 100\% \quad (2)$$
2. Adsorption Isotherms
   Data were analyzed using Langmuir and Freundlich models.
   a. Langmuir (linear form):
   $$Q = \frac{b.K.Ce}{1+K.Ce} \quad (3)$$
   $$Q = K.Ce.1/n \quad (4)$$
   Ce = equilibrium concentration of adsorbate in solution after adsorption (mg/L)
   Q = the amount of adsorbed adsorbate per adsorbent weight (mg/g)
   K = the adsorption equilibrium constant (L/mg)
   B = the maximum adsorption capacity of the adsorbent (mg/g)
   n = empirical constant
   b. Freundlich (linear form):
   $$Log\,Q = Log\,k + 1/n\,Log\,Ce \quad (5)$$
3. Determination of Reaction Order
   The adsorption kinetics were analysed using zero-, first-, and second-order models Zero-order:
   - Zero-order:
   $$K = \frac{wb - wa}{t} \quad (6)$$
   - First-order:
   $$K = \frac{\ln[wb] - \ln[wa]}{t} \quad (7)$$
   - Second-order:
   $$K = \frac{1}{t}\left(\frac{1}{[wa]} - \frac{1}{[wb]}\right) \quad (8)$$
   Wb = concentration of A at time t = 0 (ppm)
   Wa = concentration of A at time t = t (ppm)
   t = time
4. Adsorption Rate
   The adsorption rate was calculated as:
   $$v = k[A]^x \quad (9)$$
   v = Absorption Rate
   k = Absorption rate constant
   [A] = metal constant
5. Half-Life Determination
   The half-life of adsorption was estimated as:
   $$t\frac{1}{2} = \frac{1}{k[A_0]} \quad (10)$$
   t½ = halftime
   k = average constant
   $[A_0]$ = metal constant over time t = 0

III. Results and Discussions

The kinetic parameters were calculated from experimental adsorption data, as shown in Tables 1 and 2. Table 1 presents the change in Cd concentration over time (this data from our previous work) [18], while Table 2 compares the calculated rate constants for zero-, first-, and second-order reaction models.

TABLE I. Adsorption of Cadmium (Cd) by Durian Peel Biomass

Halftime	Absorbent Weight	Initial Concentration	Absorbed Concentration	% Absorbed
0	3	100	0	0
20	3	100	76	76
40	3	100	76,4	76,4
60	3	100	76,8	76,8
80	3	100	78,4	78,4

TABLE II. Rate Constant (k) Values for Different Reaction Orders

Time (min)	Zero order k (ppm/min)	First order k (min^{-1})	Second order k (ppm^{-1} min^{-1})
20	1.2	0.0137	0.0001579
40	0.59	0.0067	0.0000772
60	0.3867	0.0044	0.0000503
80	0.27	0.003	0.0000344
Average			0.00007998

Based on Table 2, the results of the analysis show that the k value tends to be constant at the second order kinetic value, which indicates that the adsorption process follows the 2nd order reaction mechanism. so that the cadmium metal reaction follows the second order reaction, where the reaction rate is directly proportional to the square of the reactant concentration. With an average reaction rate of 0.00007998 ppm^{-1} min^{-1}.

The reaction rate was determined using the second-order rate law $v = k[A]^2$. The calculated results are presented in Table 3.

TABLE III. Absorption/Reaction Rate of Cd Adsorption

Time (min)	[A] (ppm)	k (ppm^{-1} min^{-1})	v (ppm/min)
20	76	$7.998.10^{-05}$	0.462
40	76.4	7.99810^{-05}	0.467
60	76.8	7.99810^{-05}	0.472
80	78.4	7.99810^{-05}	0.492

The half-life of Cd adsorption was calculated using the second-order half-life equation:

t½= 1/(k[A0])

Substituting the known values:

t½ = 1 / (0.00007998 ppm^{-1} min^{-1} × 100 ppm)

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= 125 minutes

This indicates that 50% of the initial Cd concentration is removed within 125 minutes, which extends beyond the maximum experimental time of 80 minutes.

The kinetic results confirm that Cd adsorption using durian peel biomass follows a second-order kinetic model, with a consistent rate constant of approximately 8×10^{-5} ppm^{-1} min^{-1}. The second-order mechanism suggests that the adsorption rate is controlled by the availability of active sites on the adsorbent surface and the square of Cd ion concentration in solution. This finding is consistent with adsorption studies using other agricultural wastes such as kapok fruit peel [20], areca nut peel [21], and durian peel waste [18], all of which reported pseudo-second-order kinetics with high correlation coefficients ($R^2 > 0.99$).

The adsorption rate increased steadily with contact time, indicating that more Cd^{2+} ions occupied active sites as the system approached equilibrium. The relatively high-rate values observed after 80 minutes highlight the potential of durian peel biomass as a cost-effective adsorbent for Cd removal. Compared to conventional adsorbents such as activated carbon, durian peel offers advantages in terms of availability, cost efficiency, and environmental sustainability. The calculated half-life of 125 minutes reflects the time required to reduce Cd concentration by half under the given experimental conditions. While this half-life is relatively long compared to some high-capacity adsorbents, it is consistent with natural biosorbents, where adsorption occurs gradually due to the diffusion of ions into porous structures. Saragih (2020) reported a comparable equilibrium time (≈120 minutes) for Cd adsorption using black sand, reinforcing the finding that Cd adsorption kinetics are strongly influenced by adsorbent type and initial concentration.

The results of this study are significant not only from an environmental perspective but also from an educational standpoint. The adsorption process provides a practical example for teaching chemical kinetics in environmental and analytical chemistry courses. Students can directly relate abstract kinetic models (zero-, first-, and second order) with real-world applications in wastewater treatment. By using locally available durian peel biomass, this study also illustrates the integration of sustainable resource utilization into chemistry education, thereby strengthening contextual and eco-friendly learning approaches.

To validate these results, you can also perform an analysis using a graph by plotting the relationship between 1/[A] and time (t) can be seen in Figure 1.

From the graph data above, we can see that the relationship between 1/[A] and t forms a straight line with the equation y = 5 X 10-5 x + 0.01, which is in accordance with the characteristics of a second-order reaction, as stated by Fatimah (2013) that 1/C Vs t will form a linear line where C is the concentration of A at time (t).

From the equation, the value of k can be calculated as the slope of the line, namely $k = 5 \times 10^{-5}$ ppm^{-1} min^{-1}. This value is consistent with the calculation at 60 minutes, which is 0.0000503 ppm^{-1} min^{-1}.

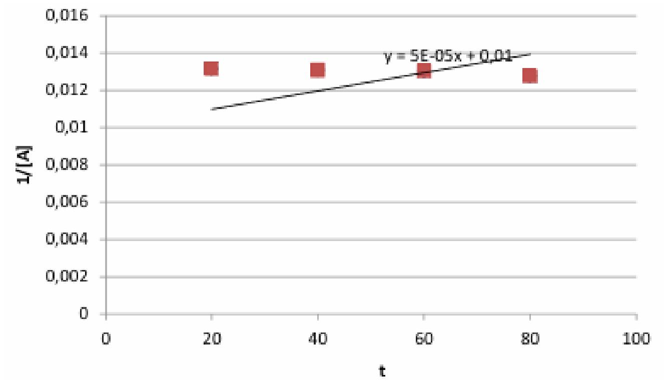

Fig. 1. Graph of the Relationship between 1/[A] and Time (t)

In addition, these findings that support this research, such as research conducted by [21] which showed that the adsorption of Cd(II) ions using adsorbents from areca nut skin follows a second-order kinetic model with a kinetic constant (k_2) of 0.422 min^{-1}.

After determining the reaction order used is order 2, then we can determine the absorption rate (v) by using the formula in equation 4.

The calculation results are presented in table 3, which shows an increase in the absorption of cadmium (Cd) metal from 0.46194407 at 20 minutes to 0.491580149 at 80 minutes, this shows that the absorption rate increases with time, this is in accordance with the second-order characteristics where the reaction rate is directly proportional to the square of the reactant concentration ([A]).

This is also in line with research conducted by [20], which also showed that the adsorption of Cd (II) using kapok fruit skin waste followed a pseudo-second-order kinetic model with a correlation coefficient (R^2) value of 0.9999. This shows very good agreement with these results.

After knowing the reaction order in this study follows the 2nd-order reaction and is strengthened using graphic data and calculations of the absorption rate (v), the half-life can be calculated using equation 5. As shown in the results of determining the half-life. The calculation results show that the half-life is 125 minutes, which means that 50% of the initial concentration of cadmium metal is absorbed within that time. This shows that the half-life that passes the experimental time is 80 minutes; this is due to the relatively low initial concentration of Cd^{2+}, so that the absorption process takes longer to reach half of the initial concentration.

This is supported by research conducted by [22] regarding the adsorption of Cd^{2+} ions using black sand as an adsorbent which also showed that the optimum contact time to reach equilibrium was 120 minutes, supporting the finding that the half-life in the Cd^{2+} adsorption system can vary depending on the initial conditions and the type of adsorbent used.

Thus, the results of this study are supported by various previous studies which show that the adsorption of Cd^{2+} ions tend to follow a second-order kinetic model, with the absorption rate increasing over time and a half-life that depends on the initial concentration and the type of adsorbent used.

IV. CONCLUSIONS

This study demonstrates that durian peel biomass (*Durio zibethinus*) is an effective bioadsorbent for the removal of cadmium (Cd) ions from aqueous solutions. Kinetic analysis showed that the adsorption process follows a second-order reaction model, with an average rate constant of 7.998×10^{-5} $ppm^{-1} min^{-1}$, indicating that the adsorption rate is proportional to the square of Cd concentration. The calculated adsorption rate increased gradually over time, ranging from 0.462 ppm/min at 20 minutes to 0.492 ppm/min at 80 minutes. The estimated half-life of 125 minutes further suggests a relatively slow but steady adsorption process, consistent with natural biosorbents.

The findings are in line with previous studies on biosorption of Cd (II) ions using various agricultural wastes and confirm the potential of durian peel biomass as a low-cost, sustainable, and eco-friendly alternative adsorbent. Beyond its environmental significance in wastewater treatment, this research also offers valuable educational insights by providing a contextual case study for teaching adsorption kinetics in chemistry. The integration of local biomass resources into environmental applications not only contributes to pollution mitigation but also promotes sustainable utilization of agricultural waste.

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