Indonesian Journal of Chemical Research

http://ojs3.unpatti.ac.id/index.php/ijcr Indo. J. Chem. Res., 14 (2), 105-115, 2026

Modification of Lead Adsorbent from Activated Carbon of Cassava Peel Waste (*Manihot esculenta*) using Sodium Alginate

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Received: June 2026
Received in revised: August 2026
Accepted: September 2026
Available online: September 2026

Abstract

The study aimed to address lead (Pb) contamination in aquatic environments by utilizing an adsorbent derived from cassava peel waste. The adsorbent was prepared by carbonizing cassava peel at 350 °C, followed by chemical activation using NaOH. To enhance its adsorption performance, the activated carbon was modified with sodium alginate. The adsorption process was evaluated to determine optimum conditions, including variations in adsorbent mass, solution pH, and contact time. Experimental results showed that the optimum conditions for Pb removal were achieved at pH 6, with 0.1 g of adsorbent and a contact time of 30 minutes. Under these conditions, the adsorbent exhibited an efficiency of 99.33% and an adsorption capacity of 1.9827 mg/g. The process followed the Langmuir isotherm model, and regeneration studies showed low recovery percentages ranging from 0.2% to 0.6%. These results indicate that cassava peel waste modified with sodium alginate is a promising, low-cost material for the removal of Pb from contaminated water systems.

Keywords: adsorbent, cassava peel, lead metal, sodium alginate

INTRODUCTION

The rapid development of the industrial sector contributes significantly to environmental problems, particularly water pollution due to the release of hazardous substances such as heavy metals. Among these, lead (Pb) is one of the most commonly detected pollutants in aquatic environments and poses serious risks to ecosystems and human health. Regulatory limits have been established to control Pb levels in wastewater; however, concentrations found in industrial effluents often exceed these limits, resulting in high toxicity to aquatic organisms. Several conventional methods such as precipitation, membrane filtration, and ion exchange have been used to remove heavy metals from wastewater. However, adsorption remains one of the most effective and environmentally friendly alternatives due to its simplicity, cost-effectiveness, and high removal efficiency (Laos & Selan 2016; Suprabawati *et al.* 2018).

Previous studies have explored various adsorbents such as activated carbon and zeolite. Activated carbon is known for its large surface area and strong adsorption ability, but its capacity is limited, and it requires periodic regeneration (Ariyani *et al.* 2017). Zeolite, although widely used due to its porous structure, shows dependence on water pH and temperature, which limits its application in some conditions (Purwoto & Nugroho 2013). These limitations have led to interest in modifying adsorbents with natural polymers such as sodium alginate. Sodium alginate, derived from brown algae, contains functional groups that enhance metal ion binding and has shown improved performance when used as a composite material in adsorption processes (Gunawan *et al.* 2020; Sailah *et al.* 2020).

In addition, agricultural biomass waste is increasingly being utilized as a raw material for activated carbon production. Cassava peel, a readily available biomass waste, has high carbon content and is considered a potential precursor for low-cost activated carbon. The production process generally includes dehydration, carbonization, and chemical activation, which helps enhance the porosity and surface area of the carbon material (Amanah 2020). The combination of cassava peel-derived activated carbon and sodium alginate modification offers a promising solution for improving the adsorption capacity and efficiency for Pb(II) removal (Laos & Selan 2016).

Several studies have demonstrated the potential of this approach. For instance, Al Idrus (2018) reported that calcium alginate microcapsules could achieve up to 96.05% adsorption efficiency for Pb(II), attributed

to their porous structure and functional groups such as –OH and C=O. Similarly, composites combining alginate with other materials like α-keratin have shown enhanced performance in metal ion adsorption (Sari *et al.* 2021).

This study aims to develop an effective adsorbent by utilizing cassava peel waste modified with sodium alginate for the removal of Pb(II) ions from liquid waste. The synthesis involves the carbonization of cassava peel followed by NaOH activation and modification with sodium alginate using $CaCl_2$ as a crosslinking agent. The performance of the adsorbent is evaluated under various conditions, including different adsorbent dosages, pH levels, and contact times. This research is expected to offer a green and cost-effective alternative for industrial wastewater treatment, and the resulting adsorbent may be applied at both laboratory and industrial scales. Compared to previous studies, the novelty of this research lies in the specific combination of cassava peel-based activated carbon and sodium alginate modification for Pb(II) adsorption, which has not yet been widely explored in an industrial context.

METHODOLOGY

Materials and Instruments

The equipment used in this study included a muffle furnace (B-One Muffle Furnace MF-1, operating at 350 °C for carbonization), an oven (Memmert UN30, set at 105 °C for drying), and a vacuum desiccator (Duran Glass Vacuum Desiccator, 250 mm) for cooling and storage. Analytical measurements were conducted using a UV-Visible spectrophotometer (Bel Photonics M51) and Atomic Absorption Spectrophotometer (AAS) (Analytik Jena contrAA 800) for Pb analysis. A Fourier Transform Infrared Spectrometer (FT-IR) (Agilent Cary 670) was used for functional group identification. Additional equipment included a magnetic stirrer (IKA C-MAG HS 7), analytical balance (Denver Instrument APX-200), 100-mesh sieve, blender (Lunalife LL-BL101), and general laboratory glassware such as pipettes (10 mL volumetric pipette), burettes (50 mL), droppers, mortar and pestle, aluminum crucibles, spatula, clamps, and retort stands.

The materials used were cassava peels (sourced locally from traditional markets in Bogor), 0.3 N and 0.1 N sodium hydroxide (NaOH), 0.1 N and 25% hydrochloric acid (HCl), 0.01 M nitric acid (HNO_3), aquadest (technical grade), sodium alginate (Na-alginate), 5% calcium chloride ($CaCl_2$), and lead(II) nitrate [$Pb(NO_3)_2$]. Other materials included solid methylene blue, 0.1 N sodium thiosulfate ($Na_2S_2O_3$), 1% starch indicator, silver nitrate ($AgNO_3$), 10% potassium iodide (KI), 0.1 N potassium dichromate ($K_2Cr_2O_7$), 0.1 N iodine (I_2), aluminum foil, and a 1,000 mg/L Pb standard solution.

Methods

Preparation of Activated Carbon from Cassava Peels (Kosim *et al.* 2022)

Fresh cassava peels were thoroughly cleaned, chopped into small pieces, and sun-dried for two days. The dried peels were then oven-dried at 120 °C for 24 hours. Carbonization was carried out in a furnace at 350 °C for 3 hours. The resulting carbon was allowed to cool in a desiccator for 10 minutes, ground using a mortar and pestle, and sieved to obtain particles with 100 mesh size.

The carbon was chemically activated by immersing it in 0.3 N sodium hydroxide (NaOH) solution for 24 hours. The sample was filtered using filter paper and washed with 0.1 N hydrochloric acid (HCl) and deionized water until a neutral pH (pH 7) was achieved. To confirm chloride removal, 1 mL of sample was reacted with 5 drops of 0.1 M silver nitrate ($AgNO_3$); the absence of turbidity indicated complete chloride elimination. Finally, the sample was oven-dried at 100 °C for 3 hours.

Yield Determination (Kosim *et al.* 2022)

Approximately 2 g of sample was carbonized at 350 °C for 1 hour in a furnace. The yield was calculated based on the mass difference before and after carbonization. Each measurement was performed in triplicate.

Moisture Content Analysis (Laos & Selan 2016)

Two grams of activated carbon were placed in a pre-weighed aluminum crucible and oven-dried at 105 °C for 3 hours. After cooling in a desiccator for 15 minutes, the crucible was weighed again to determine moisture loss. The procedure was repeated three times.

Ash Content Analysis (Mappa *et al.* 2023)

Two grams of activated carbon were placed in a porcelain crucible and incinerated in a furnace at 550 °C for 4 hours. After cooling in a desiccator for 15 minutes, the residue was weighed to determine ash content. The analysis was performed in triplicate.

Volatile Matter Determination (Haryati *et al.* 2017)

A 1–2 g sample was placed in a pre-weighed porcelain crucible and heated at 950 °C for 6 minutes in a furnace. The crucible was then cooled in a desiccator for 15 minutes before weighing. This process was repeated three times.

Methylene Blue Adsorption Test (Hatimah *et al.* 2022)

A 3 mg/L methylene blue standard solution was used to determine the maximum wavelength using a UV-Vis spectrophotometer within the 640–680 nm range. Activated carbon samples (0.005 g each) were oven-dried at 105 °C for 1 hour, placed into Erlenmeyer flasks, and mixed with 50 mL of 25 mg/L methylene blue solution. The mixtures were stirred at 100 rpm for 15 minutes, filtered, and the absorbance of the filtrate measured using UV-Vis spectrophotometry at the previously determined wavelength. All experiments were performed in triplicate and also conducted in the dark, covered with aluminum foil.

Iodine Number Determination (Laos & Selan 2016)

Activated carbon (0.5 g) was oven-dried at 105 °C for 1 hour, then added to 25 mL of 0.1 N iodine solution. The mixture was stirred at 150 rpm for 15 minutes and left to stand for another 15 minutes. A 10 mL aliquot was titrated with 0.1 N sodium thiosulfate solution using 1% starch as an indicator. The titration was continued until the blue color disappeared. All analyses were repeated three times.

Modification of Cassava Peel Activated Carbon with Sodium Alginate (Lestari 2019)

Sodium alginate powders of varying amounts were dissolved in distilled water and heated at 55 °C. To each solution, 0.5 g of Span 80 was added and homogenized, then allowed to cool. The sodium alginate solution was mixed with cassava peel activated carbon and homogenized using a magnetic stirrer. The resulting mixture was dropped into 100 mL of 5% calcium chloride solution to form beads. The beads were allowed to stand for 24 hours to complete gelation, washed with distilled water, 0.1 N NaOH, and 0.1 N HCl until neutral pH was reached, then filtered and stored at room temperature.

Preparation of Sodium Alginate Control Adsorbent (Yantyana *et al.* 2018)

Two grams of sodium alginate were dissolved in 100 mL distilled water and dropped into 100 mL of 5% calcium chloride solution to form beads. After standing for 24 hours, the beads were washed with distilled water, 0.1 N NaOH, and 0.1 N HCl until the pH reached 7, then filtered and stored at room temperature.

Determination of Optimum Adsorption Conditions: Effect of Adsorbent Dosage (Sari *et al.* 2021)

Adsorbents (cassava peel activated carbon, sodium alginate, and their composites in five formulations) were weighed at varying amounts (0.025 g to 0.1 g) and placed in Erlenmeyer flasks with 20 mL of 10 mg/L Pb solution and 1 mL of pH 7 buffer. The mixtures were stirred at 150–200 rpm at room temperature for 30 minutes. Afterward, samples were filtered, and the filtrate was analyzed using Atomic Absorption Spectrophotometry (AAS). The procedure was repeated three times.

Determination of Optimum Adsorption Conditions: Effect of pH (Saputri, 2020)

Using the optimum mass, adsorbents were added to Pb solutions at pH 3, 5, 6, 7, and 8. Each mixture was stirred at 150–200 rpm at room temperature for 30 minutes, filtered, and analyzed using AAS. All measurements were conducted in triplicate.

Determination of Optimum Adsorption Conditions: Effect of Contact Time (Khoiriyah *et al.* 2016)

The optimum mass of each adsorbent was added to 20 mL of 10 mg/L Pb solution at the optimum pH. Contact time variations were 15, 30, 45, 60, and 75 minutes. Stirring was done at 150 rpm at room temperature. After filtration, the filtrates were analyzed using AAS. The procedure was repeated three times.

Fourier Transform Infrared Spectroscopy (FT-IR) Analysis

FT-IR analysis was conducted on cassava peel activated carbon, sodium alginate, and the best composite formulation using a Cary 670 FT-IR Spectrometer. Spectra were recorded in the 4000–500 cm^{-1} range with a resolution of 4 cm^{-1}. The spectrometer was equipped with a Deuterated Lanthanum α-alanine-doped TriGlycine Sulphate (DLaTGS) detector and operated with an interferometer scanning speed of approximately 5 kHz.

Adsorption Capacity Test (Saputri, 2020)

After determining the optimum conditions (adsorbent dose, pH, and contact time), the adsorption capacity for Pb was analyzed. Adsorbents were contacted with Pb solution under optimum conditions. The filtrates were analyzed using AAS. All experiments were conducted in triplicate.

Adsorption Isotherm Analysis (Saputri 2020)

The best adsorbent formulation, along with cassava peel activated carbon and sodium alginate, was tested with Pb standard solutions at various concentrations (5, 10, 15, 30, and 45 ppm) at optimum pH and contact time. The isotherm models used were Langmuir and Freundlich. Data were plotted accordingly to determine the adsorption behavior.

Adsorbent Regeneration (Widayatno *et al.* 2017)

The best formulation, along with cassava peel activated carbon and sodium alginate, was regenerated by immersion in 0.01 M nitric acid (HNO_3) for 1 hour with stirring. After desorption, adsorbents were washed with deionized water and oven-dried at 60 °C. Their adsorption efficiency was re-evaluated by repeating the Pb adsorption test using the same conditions and measuring the filtrate with AAS. Each test was repeated three times.

Data Analysis

The equation used must be written centered with the numbering as in the following example:

$$\text{Yield (\%)} = \frac{\text{weight of activated carbon (g)}}{\text{sample weight (g)}} x100 \quad (1)$$

$$\text{Moisture content (\%)} = \frac{\text{Initial weight (g)} - \text{Final weight (g)}}{\text{Initial weight (g)}} \; x\; 100 \quad (2)$$

$$\text{Ash content (\%)} = \frac{\text{Initial sample weight (g)}}{\text{Total ash weight (g)}} \text{ x } 100 \quad (3)$$

$$\text{Volatile Matter Content (\%)} = \frac{\text{bobot awal karbon (g)} - \text{bobot akhir karbon (g)}}{\text{bobot awal karbon (g)}} \; x\; 100\% \quad (4)$$

$$\text{Methylene Blue Adsorption Capacity } \left(\frac{\text{mg}}{\text{g}}\right) = \frac{X_0 - X_1}{w} \text{x V} \quad (5)$$

Explanation:
X_0 = Initial concentration (mg/L)
X_1 = Final concentration (mg/L)
V = Volume of methylene blue solution (L)
w = Weight of the sample (g)

$$\text{Iodine Adsorption Capacity (mg/g)} = \frac{\left(V1 - \left(\frac{V_2 X N_2}{N_1}\right)\right)}{m} \; x\; 12{,}69\; x\; fp \quad (6)$$

Explanation:
V_1 = Volume of iodine (mL)
N_1 = Normality of iodine solution (N)
V_2 = Volume of $Na_2S_2O_3$ (mL)
N_2 = Normality of $Na_2S_2O_3$ (N)
12.69 = Iodine content equivalent per 1 mL of $Na_2S_2O_3$
fp = Dilution factor
m = Weight of activated carbon (g)

$$\text{Adsorption Capacity } (Q_e) \left(\frac{\text{mg}}{\text{g}}\right) = \frac{C_0 - C_a}{m} \text{ x V} \quad (7)$$

Explanation:
Q_e = Adsorption capacity (mg/g)
C_0 = Initial concentration (mg/L)
C_a = Final concentration (mg/L)
V = Volume of metal solution in contact with adsorbent (L)
m = Weight of adsorbent (g)

Langmuir Adsorption Isotherm:

$$\frac{Ce}{Qe} = \frac{1}{aK} + \frac{1}{a} \text{ Qe}$$

Freundlich Adsorption Isotherm:

$$\text{Log Qe} = \text{Log k} + \frac{1}{n} \text{ Log Ce}$$

Explanation:
Q_e = Amount of adsorbate adsorbed per unit weight of adsorbent (mg/g)
x = Mass of adsorbed substance (mg)
a = Maximum adsorption capacity on the solid phase
K = Equilibrium constant (L/mg)
n = Empirical constant

RESULTS AND DISCUSSION

Yield of Activated Carbon from Cassava Peel

Cassava peels were processed to produce activated carbon through a series of steps including dehydration, carbonization, and chemical activation. Initial drying was performed under sunlight for two days, followed by oven drying at 120 °C for 24 hours to eliminate moisture content and stabilize the structure (Subroto *et al.* 2022). Carbonization was conducted at 350 °C to convert the dried biomass into porous char. The resulting material was ground and sieved through a 100-mesh filter to obtain uniform particle size. Chemical activation was performed using 0.3 M NaOH, followed by washing with 0.1 N HCl and distilled water until neutral pH was achieved. A chloride test using 0.1 M $AgNO_3$ was conducted to confirm the removal of residual chloride ions (Gunawan *et al.* 2020)

This process aimed to determine the efficiency (yield) of activated carbon production from cassava peel, particularly to identify the effect of NaOH activation on carbon yield. The rationale for selecting a carbonization temperature of 350 °C was to preserve the structure of the material and generate more pores, while the use of NaOH as an activating agent was intended to increase the porosity and surface area of the final product (Firnandi *et al.* 2023).

The highest yield obtained was 55.61% after activation with NaOH solution, indicating the effective conversion of cassava peel into activated carbon. This yield is relatively high, reflecting minimal mass loss and optimal structural integrity during carbonization

and activation (Sailah *et al.* 2020). Activated carbon generally possesses a porous structure and a high specific surface area, which contributes to its adsorption performance (Rafli *et al.* 2021). The effective removal of impurities, as confirmed by the absence of AgCl precipitate in the chloride test, indicates a high degree of material purity and stability (Parmadi *et al.* 2025).

Moisture Content of Activated Carbon from Cassava Peel

Moisture content was determined by drying the activated carbon sample at 105 °C for 3 hours in an oven, followed by cooling in a desiccator for 15 minutes. The purpose of this test was to evaluate the amount of water still retained in the pores of activated carbon. Excess moisture can reduce adsorption capacity by filling the pores that should absorb other molecules (Gunawan et al., 2020). The result showed a moisture content of 4.44%, which meets the SNI 06–3730–1995 standard for activated carbon, with a maximum of 15%. This low value indicates that most water was successfully removed, and the porous structure remained intact for optimal adsorption (Utami *et al.* 2024).

Ash Content of Activated Carbon from Cassava Peel

The sample was heated in a furnace at 550 °C for 4 hours to burn off all volatile matter. It was then cooled in a desiccator to prevent moisture absorption. Ash content indicates the presence of non-combustible minerals left in the activated carbon. High ash levels can block pores and reduce surface area, thereby lowering adsorption efficiency. The ash content obtained was 5.84%, which is below the SNI 06–3730–1995 limit of 10%. This shows that the activation process was effective in reducing inorganic residue, and the resulting activated carbon is of acceptable quality (Hadi *et al.* 2024).

Volatile Matter Content of Activated Carbon from Cassava Peel

Volatile matter was measured by heating the sample at 960 °C for 6 minutes, followed by cooling in a desiccator to prevent moisture re-adsorption. This test aimed to determine the amount of organic compounds that were not fully decomposed during carbonization. Excess volatile content can hinder adsorption by covering the surface and blocking pores. The activated carbon showed a volatile content of 16.30%, which complies with the SNI 06–3730–1995 maximum of 25%. This indicates that most volatile components were successfully removed, allowing better pore development and enhancing adsorption potential (Habibi *et al.* 2024).

Methylene Blue Adsorption Capacity of Activated Carbon from Cassava Peel

The activated carbon was tested for its ability to adsorb methylene blue (MB) using UV-Vis spectrophotometry at 665 nm on Figure 1, after mixing with a 25 mg/L MB solution and stirring for 15 minutes. Two conditions were used: with and without light exposure. Methylene blue adsorption evaluates the carbon's ability to remove large, positively charged organic molecules common in wastewater. Efficient adsorption requires activated carbon with sufficient pore size and surface functional groups like –OH and –COOH (Latupeirissa *et al.* 2018). This value is consistent with most scientific references, which state that methylene blue has a maximum wavelength between 660 and 668 nm had well-developed pores and active functional groups effectively captures MB molecules.

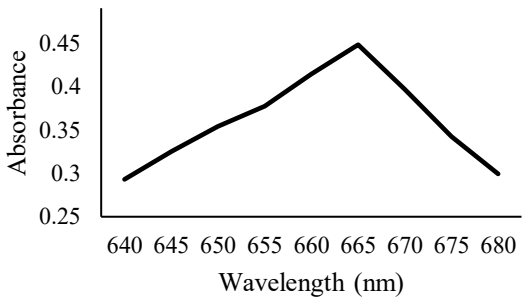

Figure 1. Maximum wavelength of methylene blue

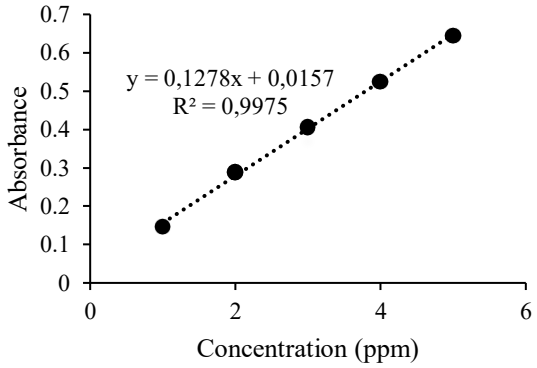

Figure 2. Standard Curve Graph of Methylene Blue

Based on Figure 2, absorbance measurements of the standard methylene blue solution yielded a linear relationship represented by the equation y = 0.1278x + 0.0157, with a regression coefficient R^2 = 0.9975. An

R^2 value close to 1 indicates a very strong and accurate correlation between the data and the linear model, demonstrating that the standard curve is reliable. The higher the R^2 value, the smaller the deviation of data points from the regression line, and the greater the standard curve's ability to consistently provide accurate results when used to determine methylene blue concentration based on absorbance values in quantitative analysis (Rizky & Silalahi 2022).

The different light intensity conditions used in this treatment were intended to evaluate the effect of light exposure during the chemical activation stage on the adsorption quality of the activated carbon. The results show that variations in lighting did not affect the adsorption capacity (Priyanto *et al.* 2021). This finding indicates that the carbon possesses an effective porous structure and surface functional groups capable of capturing methylene blue molecules, which are basic dyes with positive charges (Hatimah *et al.* 2022). This value of 200,4838 mg/g meets the minimum standard specified by SNI 06-3730-1995, which is 120 mg/g.

The adsorption mechanism of methylene blue on activated carbon occurs through electrostatic interactions between the positively charged methylene blue, as a cationic compound, and the negatively charged surface of activated carbon, derived from surface functional groups such as carboxylate ($–COO^-$) and hydroxyl (–OH) (Rahayu *et al.* 2020). This charge interaction facilitates the adhesion of methylene blue molecules to the surface of the activated carbon. Another interaction involved in the adsorption mechanism is hydrogen bonding, which forms between the polar group $–NH_2$ of methylene blue and hydroxyl groups on the surface of the activated carbon. This interaction helps stabilize the attachment of methylene blue molecules following the initial electrostatic attraction (Hatimah *et al.* 2022).

The adsorption mechanism is further strengthened by π–π stacking interactions between the aromatic structure of methylene blue and the aromatic domains of the activated carbon. These interactions occur when the π orbitals of the methylene blue aromatic rings align and stack with those on the carbon surface, forming stable non-covalent bonds on Figure 3. This π–π interaction enhances the overall adsorption stability and increases the binding affinity of methylene blue to the adsorbent surface, while also contributing to the selectivity of the adsorbent towards aromatic or conjugated dye molecules (Ren *et al.* 2021). Such interactions occur because the aromatic rings in activated carbon can align and overlap with the aromatic structure of methylene blue, facilitating stronger non-covalent bonding. This not only accelerates the adsorption rate but also improves resistance to desorption under varying environmental conditions. Furthermore, the presence of well-developed aromatic domains in activated carbon promotes multi-layer adsorption, which maximizes the utilization of available surface sites. As a result, activated carbon with rich aromatic domains demonstrates superior performance in the removal of methylene blue.

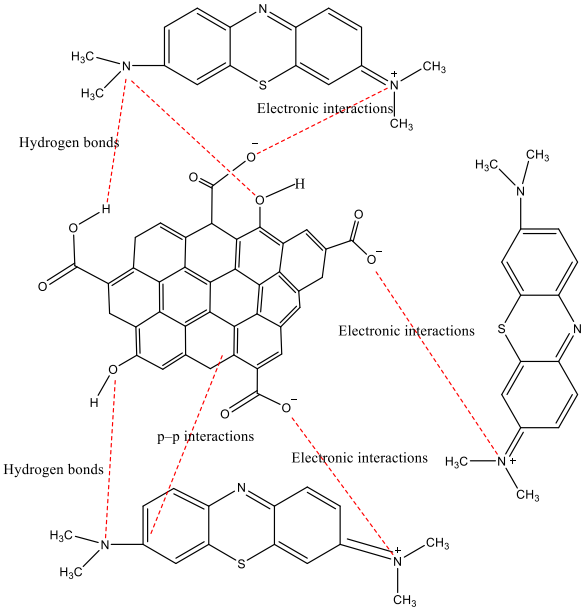

Figure 3. Adsorption reaction mechanism of methylene blue on cassava peel-based activated carbon (Ren et al., 2021)

Iodine Adsorption Capacity of Activated Carbon from Cassava Peel

Activated carbon was mixed with iodine solution and stirred for 15 minutes, followed by titration with sodium thiosulfate using starch as an indicator to determine how much iodine was adsorbed. The iodine number was used as an indicator of the adsorption characteristics and porous structure of the activated carbon (Hidayat et al., 2019). It reflects the material's ability to adsorb small molecules, making it a key indicator of carbon quality. The iodine adsorption was 188.61 mg/g, far below the SNI minimum of 750 mg/g. This suggests that the carbon had limited microporous surface area. However, the presence of functional groups such as –COOH and –OH may still support adsorption of specific substances like heavy metals (Rizky & Silalahi 2022)

The adsorption mechanism occurring with activated carbon, as shown in Figure 4, indicates that the initial interaction is dispersive forces or van der

Waals interactions. Polar functional groups such as –OH and –COOH can form hydrogen bonds with I_3^- ions, which strengthen the attachment of iodine to the carbon surface. In this mechanism, hydrogen bonding occurs between the electropositive –OH group, which is attracted to the lone electron pairs of the electronegative iodine atoms. These molecular bridges link the polar groups on activated carbon to iodine species in Figure 4 (Pan *et al.* 2023).

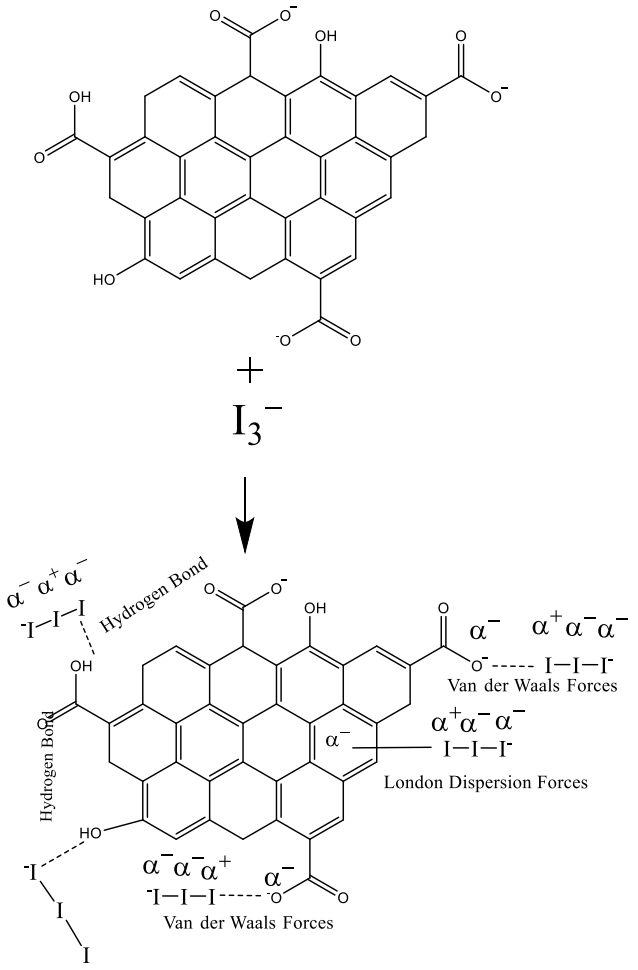

Figure 4. Adsorption reaction mechanism of iodine on cassava peel-based activated carbon (Pan et al., 2023).

Optimum Adsorbent Mass Effect on Pb(II) Adsorption

Five variations of adsorbent mass using cassava peel activated carbon, sodium alginate, and their combinations were tested for Pb^{2+} adsorption at pH 7 and 10 mg/L Pb^{2+} solution in Figure 5. The mixture was stirred at 150 rpm for 30 minutes, then filtered, and Pb^{2+} concentration was measured using SSA. To determine how increasing adsorbent mass affects adsorption capacity and efficiency. More adsorbent mass provides more active sites but may reduce capacity due to saturation when the adsorbate becomes limited. Formulation F3 (carbon + alginate) consistently showed the highest efficiency. At 0.1 g, F3 reached 99.52% efficiency, while plain carbon and alginate reached only 67.24% and 92.12%. Despite a slight drop in capacity at higher mass, efficiency improved due to a larger proportion of Pb^{2+} being captured (Hatimah *et al.* 2022).

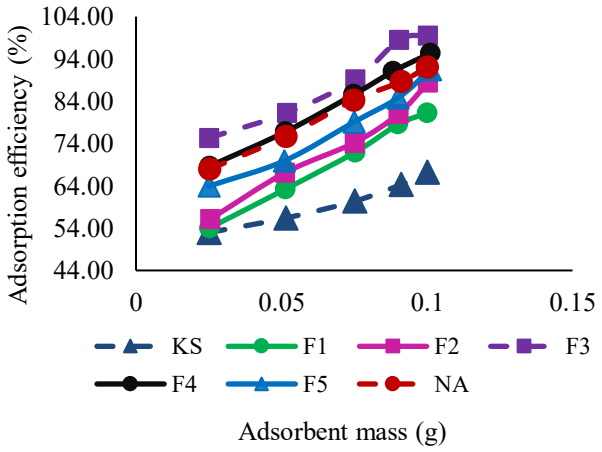

Figure 5. Effect of adsorbent mass on Pb adsorption

Optimum Adsorbent for Pb(II) Adsorption

Adsorption tests were conducted at pH 3–8 using the same adsorbents. The goal was to see how pH affects the performance of each material, especially formulation F3. pH affects the ionization of surface functional groups and the electrostatic interaction between the adsorbent and Pb^{2+}. Low pH leads to proton competition and charge repulsion, while neutral pH favors binding. pH 6 yielded the best results, with F3 reaching 1.9825 mg/g capacity and 99.42% efficiency. At low pH, adsorption was suppressed due to proton competition. At high pH, $Pb(OH)_2$ formed and reduced free Pb^{2+}. F3 outperformed the individual components across all pH levels in Figure 6.

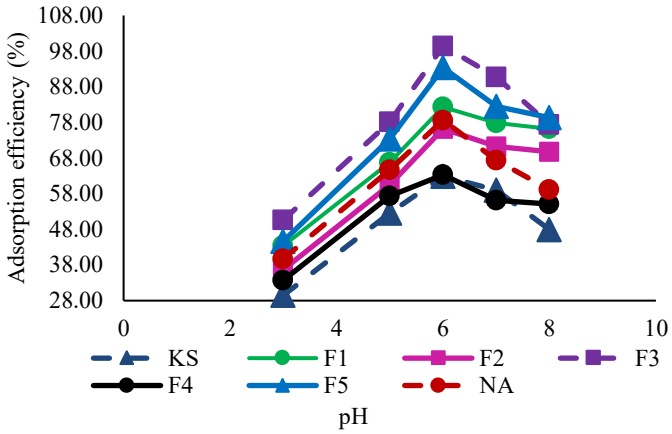

Figure 6. Effect of pH on Pb adsorption

Optimum Contact Time Effect on Pb(II) Adsorption

Adsorption was observed at contact times of 15 to 75 minutes. Pb^{2+} concentrations were measured post-filtration to assess adsorption performance over time. The optimal time was determined as the time at which maximum adsorption occurs before reaching equilibrium or desorption begins (Ilmanafia & Sudarminto 2022). Maximum adsorption was at 30 minutes. F3 reached 1.9827 mg/g and 99.33% efficiency. Beyond 30 minutes, performance decreased, likely due to site saturation and desorption. Carbon alone only reached 1.5695 mg/g (78.79%). The F3 blend proved most efficient, showing the benefit of combining alginate's stability with carbon's surface area in Figure 7.

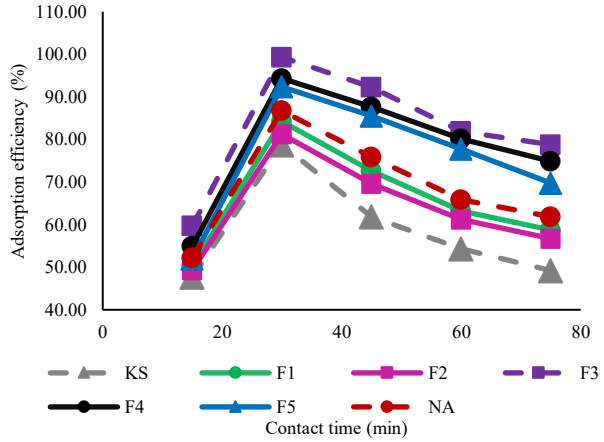

Figure 7. Effect of Time on Pb adsorption

Adsorption Isotherm of Pb(II)

Adsorption behavior of Pb^{2+} ions was modeled using Langmuir and Freundlich isotherms on cassava peel activated carbon, sodium alginate, and their composite (F3). Equilibrium data were fitted to obtain constants such as adsorption capacity (α, Kf), interaction energy (β), and correlation coefficients (R^2). To understand the adsorption mechanism and determine whether the process occurs on a homogeneous surface (Langmuir) or a heterogeneous surface (Freundlich) (Imani *et al.* 2020). This analysis helps in optimizing industrial-scale processes by selecting the best-fitting model for adsorbent performance. The Langmuir model showed a better fit with higher R^2 values (0.9884–0.9968), indicating monolayer adsorption with uniform surface sites. Maximum adsorption capacity (α) ranged from 8.1967–8.7260 mg/g. The F3 composite had the highest β value (1.1499 L/mg), suggesting the strongest adsorbate–adsorbent interaction.

In contrast, the Freundlich model had lower R^2 (0.8239–0.8890). Though Kf values were close (3.3258–3.4546), the n values >1 indicated favorable physical adsorption. However, the Langmuir model better explained Pb^{2+} adsorption behavior on all adsorbents, confirming monolayer binding as the dominant mechanism in Table 1.

Table 1. Results of adsorption isotherm parameter calculations

Isoterm	Parameter	KS	NA	F3
Langmuir	α (mg/g)	8,4175	8,7260	8,1967
	β (L/mg)	0,9770	0,8741	1,1499
	R^2	0,9884	0,9936	0,9968
Freundlich	Kf	3,4277	3,3258	3,4546
	(mg/L)	1,9168	1,8546	2,0517
	n	0,8239	0,889	0,8671
	R^2			

FT-IR Characterization of Adsorbents

FT-IR spectroscopy was performed on cassava peel activated carbon, sodium alginate, and F3 composite to identify functional groups on each material. The spectra were analyzed in both the functional group region (4000–1500 cm^{-1}) and fingerprint region (1500–500 cm^{-1}). To determine the active functional groups responsible for Pb^{2+} adsorption and confirm chemical changes due to material synthesis and composite formation. Cassava peel carbon showed –OH (3343 cm^{-1}), CH_2 (2884 cm^{-1}), C=O (1741 cm^{-1}), and aromatic C=C (1516 cm^{-1}). The fingerprint region confirmed aromatic structures (836, 761 cm^{-1}). Sodium alginate displayed –OH (3303 cm^{-1}), CH_2 (2937 cm^{-1}), and COO^-/Na^+ related bands (1417, 1031 cm^{-1}). Composite F3 combined both signatures, including strong O–H (3343 cm^{-1}), C=O (1631 cm^{-1}), and ether/COOH groups in the fingerprint region (1089, 1033 cm^{-1}),

confirming successful integration. The FT-IR results support the presence of polar and reactive functional groups that contribute to physical and chemical adsorption interactions, enhancing Pb^{2+} uptake (Iskandar 2017).

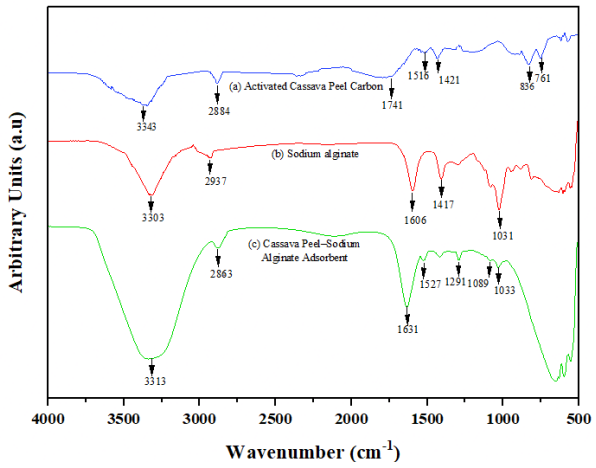

Figure 8. FT-IR Characterization Results

Table 2. FT-IR characterization results

Functional Group	Wavenumber (cm^{-1}) KS	NA	F3	Literature Wavenumber (cm^{-1})
O–H *stretching*	3343	3303	3343	3200-3600 (Perdani et al., 2021)
CH_2 *stretching*	2884	2937	2884	2850-2960 Marhaini et al., 2021)
C=C *stretching*	1516	-	1516	1500-1600 (Lestari 2019)
C=O *stretching*	1741	1606	1741	1690-1700 (Astuti et al., 2022)
C–H *bending*	1421	-	1421	1350-1470 (Perdani et al. 2021)
C–H *out-of-plane bending*	836	-	836	675-870 Marhaini et al., 2021)
=C–H *out-of-plane bending*	761	-	761	675-870 Marhaini et al., 2021)
Na *isomer stretching*	-	1417	3303	1410-1420 Maharani et al., 2022)
COOH *stretching*	-	1031	1606	1000-1100 Paramitha et al. 2024)
C–O *stretching*	-	-	1417	1410-1420 Alaydrus et al., 2023)

Adsorbent Regeneration

After adsorption, the used adsorbents were regenerated by immersing them in 0.01 M HNO_3 for 1 hour with stirring to desorb Pb^{2+} ions. They were then rinsed with distilled water to remove acid residues and dried at 60 °C. To evaluate the reusability and durability of each adsorbent. Acid regeneration tests indicate the material's potential for long-term application and economic feasibility in wastewater treatment. All adsorbents retained high efficiency after three regeneration cycles. The F3 composite showed the highest regeneration percentage, maintaining over 90% efficiency with a small decline of 0.2–0.6% per cycle. This suggests excellent structural stability and strong adsorbate binding that remains effective through multiple uses (Suprabawati *et al.* 2018). The decrease in adsorption efficiency remained within a tolerable range (<5%).

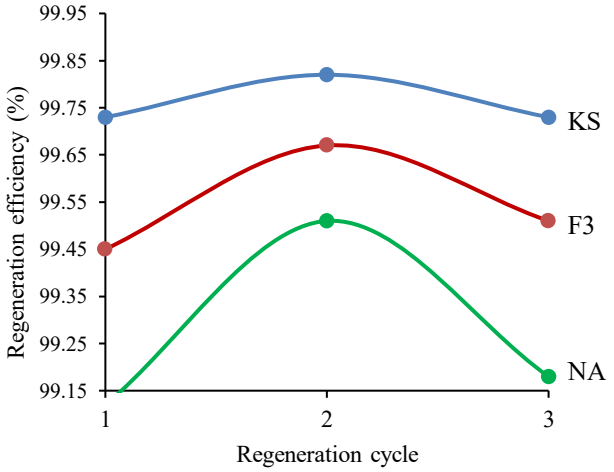

Figure 9. Regeneration results diagram

CONCLUSION

The results demonstrated that activated carbon derived from cassava peel possesses good quality and generally meets the SNI 06-3730-1995 standard, except for its iodine adsorption capacity, which fell below the required minimum. The most effective Pb(II) adsorption occurred at pH 6, using 0.1 g of adsorbent and 30 minutes of contact time. The adsorption capacity and efficiency of cassava peel activated carbon were 0.9495 mg/g and 78.79%, respectively, while sodium alginate reached 1.0426 mg/g and 86.27%, and the cassava peel–sodium alginate composite (F3) achieved the highest values at 1.9827 mg/g and 99.33%. All three adsorbents followed the Langmuir isotherm model with R^2 values of 0.9884, 0.9968, and 0.9936, respectively, indicating monolayer adsorption on homogeneous surfaces.

ACKNOWLEDGMENT

The authors would like to express their deepest gratitude to Allah subḥānahu wa ta'ālā for His guidance and blessings throughout the completion of this research entitled "Modification of Lead Adsorbent from Cassava Peel (Manihot esculenta) Waste-Based Activated Carbon Using Sodium Alginate", conducted from December 2024 to February 2025. Appreciation is also extended to Dr. Farida Laila, S.Si., M.Si., for her insightful feedback during the final project examination.

This research was independently funded and did not receive any specific grant from public, commercial, or not-for-profit funding agencies. The authors are also grateful to the Department of Chemical Analyst IPB University, and PT BMT Asia Indonesia, for providing research facilities and a supportive academic environment. It is hoped that the findings of this study will contribute to the advancement of wastewater treatment technologies and serve as a reference for future studies in the field.

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