Evaluation of The Adsorptive Capacity of Cassava Peels in The Removal of Some Heavy Metals and Microbes in Contaminated Water

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Abstract
Access to clean and safe water remains a major environmental and public health challenge, particularly in developing regions where contamination by heavy metals and microbial pathogens is prevalent. This study investigated the effectiveness of acid-modified cassava peels (Manihot esculenta) as a low-cost and sustainable adsorbent for the removal of selected heavy metals (Cd, Pb, Cr, and Ni) and microbial contaminants from polluted water. Batch adsorption experiments were conducted under varying experimental conditions of pH, adsorbent dosage and contact time. For the heavy metals and microbial contaminants, removal efficiency increased with increasing contact time and adsorbent dosage with optimum remediation performance occurring at neutral pH (7.0). Equilibrium adsorption data were analyzed using both Langmuir and Freundlich isotherm models. The data exhibited a superior correlation with the Freundlich model across all target metals (R^2: Cd = 0.999, Pb = 0.999, Cr = 0.997, Ni = 0.998) compared to the Langmuir model (R^2: Cd = 0.982, Pb = 0.962, Cr = 0.996, Ni = 0.992) confirming multilayer adsorption mechanism onto heterogeneous binding sites. Kinetic analysis showed that the pseudo-second-order model provided the best fit for Cd, Pb and Ni (R^2: Cd = 0.9932, Pb = 0.9932, Ni = 0.9877), whereas Cr showed comparable fits under the pseudo-first-order (R^2 = 0.9355) and pseudo-second-order (R^2 = 0.9318) models. The biosorbent demonstrated significant efficacy against Total Coliform and E. coli. The findings establish that acid-modified cassava peel is an efficient, eco-friendly, and cost-effective biosorbent for simultaneous removal of heavy metals and microbial contaminants from water, with strong potential for application in wastewater treatment, particularly in developing regions.

Keywords: *Cassava peel biosorbent; Acid modification; Heavy metal remediation; Adsorption isotherms; Sorption kinetics; Microbial inactivation; Multi-contaminant water purification.*

1. Introduction

Clean water is one of the basic needs that is very important for humans, especially in fulfilling domestic and industrial activities. The need for clean water increases with population growth every year. This phenomenon is in line with the unavailability of safe clean water. By 2050, more than half of the global population (57%) of people will live in a country or region that will experience a water crisis [1]. Environmental pollution, especially water pollution, is a problem in the availability of clean water. Examples of common environmental contaminants are heavy metals such as mercury, lead, copper, etc. [2].

The rapid urbanization and industrialization in the last decade have made water pollution a huge global problem [3]. A large number of inorganic and organic contaminants discharged from anthropogenic as well as natural sources have degraded the quality of water resources at a very quick rate. Inadequate sewage treatment, chemical wastes, industrial effluents, petroleum refining wastes, metal plating, mining, fertilizers and pesticides used in agricultural activities, radioactive waste material etc. are the main source of discharge of heavy metals and dyes mainly responsible for water pollution [3].

There may be various types of contaminants in water, such as viruses, bacteria, organic particles, dyes and heavy metal ions, e.g. Cu^{2+}, Cr^{6+}, Pb^{2+}, Co^{2+}, Cd^{2+}, Zn^{2+}, As^{3+}, Ni^{2+}, and Hg^{2+} etc. World Health Organization (WHO) has established waste water regulations to trim down human and environmental contact to dangerous chemicals [4]. What distinguishes heavy metals from other toxic substances is their persistence in the environment (they are not biodegradable) and the possibility of their accumulation in living tissues, leading to their concentration in the food chain. The accumulation of heavy metals in the human body can cause very serious adverse effects, such as skin diseases, brain damage, anemia, liver damage, kidney failure, ulcers, and hepatitis [5]. Heavy metals are also carcinogenic and even their trace amounts can lead to many health problems in humans [6]. Moreover, the presence of these pollutants in groundwater and wastewater used for the irrigation of agricultural land contributes to their increased content in soil and vegetables, causing negative health effects for their consumers [7].

Moreso, drinking of water contaminated with microbe (bacteria) can cause health problems such as diarrhea, typhoid, hepatitis B and C, stomach, eye, skin and intestinal infections, which may be fatal. Owing to harmful effects, it is necessary to remove bacteria from potable and wastewater. Various methods have been adopted to remove bacteria from aqueous solutions including filtration, sedimentation, centrifugation, coagulation and adsorption. All these methods have many disadvantages, including sludge formation, production of secondary pollutants and high operating costs. One of the most useful indicators of water pollution is the total coliform count [8], and *Escherichia coli*, being a predominant microorganism in human excreta, serves as an excellent indicator for fecal pollution in water [9].

Many methods available for the removal of pollutants from aqueous solution, include chemical precipitation, ion exchange, membrane separation process, biological degradation, chemical oxidation, solvent extraction, and adsorption. However, these methods have several disadvantages such as limited metal concentrations specificity, generation of huge toxic sludge and high capital costs [10]. On the contrary, adsorption is found to be the most effective and prolific technique due to its convenience, cost effectiveness, ease of operation, high adsorption capacities and versatility, which explain why the adsorption method is more economical for heavy metals removal. Adsorption emerges out to be better alternative in removal of heavy metals because of its low operating cost [11]. This treatment process is favorable even at low concentration of heavy metals in waste water stream.

Utilization of low-cost biosorbents with high metal-binding capacities has been studied widely [12]. These include a variety of biomaterials such as microalgae, bacteria specie, fungal species, sawdust and plant materials [13]. Use of different biosorbents from agricultural waste such as walnut shells, potato peel, rice straw, sesame and tea waste in both, original and modified forms, are an important research focus [13]. Such studies have commonly emphasized the possibility of overcoming disposal issues associated with the specific agricultural waste materials by utilizing them as biosorbents. However, the use of untreated agricultural wastes as adsorbents can also fetch a number of problems such as small adsorption ability, elevated chemical oxygen demand (COD) and biological chemical demand (BOD) as well as total organic carbon (TOC) due to discharge of soluble organic compounds contained in the plant

materials [14]. Consequently, plant wastes require to be modified or treated ahead of being applied for the cleansing of heavy metals.

Cassava (*Manihot esculenta*), is a major staple crop cultivated by most peasants and smallholder farmers in Nigeria and other tropical African countries [15]. Cassava processing generates large quantity of solid as well as large volumes of liquid wastes. Wastes generated from cassava production and processing include the leaves, stems, peels, wastewater and starch bagasse [16]. Cassava peel as waste is very easy to obtain and the price is low so it has the potential to use as an adsorbent material [17]. Based on laboratory analysis, cassava peel contains 56.82% α-cellulose, 21.72% lignin, and fiber length of 0.05 – 0.5 cm [18]. According to Zubair et al. [19], cassava peel can be used as an adsorbent to reduce Cr metal in COD wastewater with an adsorption capacity of 0.6911 mg/g. Moreso, cassava peel can be used as an adsorbent to reduce Cr in COD wastewater with an adsorption capacity of 0.0707 mg/g [20]. Water contamination by heavy metals and microbes remains a critical global issue, especially in developing and rural areas. Traditional treatments are frequently insufficient or too expensive in settings with limited resources. This study investigates cassava peels, an abundant agricultural waste, as a sustainable and cost-effective adsorbent for simultaneous heavy metal and microbial removal from water. The aim of this research is to evaluate the effectiveness of cassava peels as a low-cost, sustainable adsorbent for the simultaneous removal of heavy metals and microbes from contaminated water. The objectives were to prepare acid-modified cassava peel (*Manihot esculenta*) as a low-cost adsorbent; to evaluate the effects of pH, dosage, contact time, and initial concentration on Cd, Pb, Cr, and Ni removal; to determine Langmuir and Freundlich isotherms for Cd, Pb, Cr, and Ni adsorption; to study adsorption kinetics using pseudo-first-order and pseudo-second-order models; and to assess removal of Total Coliform and *Escherichia coli* at varying dosages.

2. Materials and Methods

2.1 Materials

Chemicals

The study employed analytical grade chemicals including distilled water, sulfuric acid (H_2SO_4), sodium hydroxide (NaOH), cadmium nitrate ($Cd(NO_3)_2$), lead nitrate ($Pb(NO_3)_2$), nickel (II) chloride ($NiCl_2$), chromium (III) chloride ($CrCl_3 \cdot 6H_2O$). All reagents were used without further purification and prepared using distilled water to ensure purity and consistency in the experiment.

Apparatus/Equipment

The equipment used included beakers, volumetric flasks, measuring cylinders, analytical balance (±0.1 mg), funnels, mechanical grinder, orbital shaker, laboratory oven, pH meter, Atomic Absorption Spectrophotometer (AAS), and Whatman No. 1 filter paper. All glassware was washed with distilled water and dried before use.

2.2 Methods

Preparation of Cassava Peel Adsorbent

Cassava peels (*Manihot esculenta*) were obtained from a farm in Etche, Rivers State, Nigeria. The cassava peels were thoroughly washed with distilled water to remove dirt, dust, and other impurities. This cleaning process was repeated several times to ensure the peels were free from external contaminants that might interfere with the adsorption process.

After washing, the peels were spread out and air-dried at room temperature for 24 hours to remove surface moisture. Following air drying, the peels were transferred to a laboratory oven and dried at a temperature of 85°C for another 24 hours. This oven-drying step ensured that the

peels became very dry and crispy, facilitating the subsequent grinding process and ensuring a consistent moisture content across all samples.
20 ml of H_2SO_4 solution was transferred into a conical flask containing crushed adsorbent and allowed to shake or stand for 4 hrs to enhance the breakdown after which it was decanted and dried with clean water. Then oven dried at 105°C, powdered and used for adsorption process.

Preparation of Metal Ion Solutions
Stock solutions (1000 mg/L) of Cd, Pb, Cr, and Ni were prepared by dissolving appropriate quantities of their respective salts in distilled water. Working solutions (10–50 mg/L) were prepared by serial dilution using:

$$C_1V_1 = C_2V_2 \quad (1)$$

where C_1 and C_2 are the initial and final concentrations, and V_1 and V_2 are the corresponding volumes.

Batch Adsorption Studies
Batch adsorption experiments were carried out using 20 mL of metal solution and 0.2 g of cassava peel adsorbent in 100 mL beakers. The mixtures were agitated at 200 rpm for 60 minutes. After agitation, the samples were filtered using Whatman No. 1 filter paper, and the filtrates were analyzed using AAS. The percentage removal of metal ions was calculated as:

$$\%Removal = \frac{C_0 - C_e}{C_0} \times 100 \quad (2)$$

The adsorption capacity at equilibrium (q_e) was calculated using:

$$q_e = \frac{V(C_0 - C_e)}{m} \quad (3)$$

where C_0 and C_e are initial and equilibrium concentrations (mg/L), V is solution volume (L), and m is adsorbent mass (g).

Effect of pH
The effect of pH was studied by adjusting the pH of 20 mL of 10 mg/L metal solution from pH 4 to 9 using 0.1 M H_2SO_4 and NaOH. A constant adsorbent dosage of 0.2 g was used. The mixtures were agitated for 60 minutes, filtered, and analyzed.

Effect of Adsorbent Dosage
Adsorbent dosage was varied from 0.2 to 1.0 g while maintaining constant solution volume (20 mL) and concentration (10 mg/L). The mixtures were agitated, filtered, and analyzed.

Effect of Contact Time
Contact time was varied (30, 60, and 90 minutes) at constant adsorbent dose (0.2 g), concentration (10 mg/L), and pH 7. Samples were filtered and analyzed after each interval.

Effect of Initial Metal Concentration
Initial metal concentration was varied from 10 to 50 mg/L using a fixed adsorbent dose (0.2 g) and volume (20 mL). The mixtures were agitated for 60 minutes and analyzed.

Adsorption Isotherm and Kinetic Studies
Adsorption isotherm and kinetic models were applied to describe the equilibrium behavior and rate of adsorption of Cd, Pb, Cr, and Ni onto cassava peel adsorbent. The experimental data obtained were fitted to Langmuir and Freundlich isotherm models, as well as pseudo-first-order and pseudo-second-order kinetic models.

Langmuir isotherm model. The Langmuir isotherm assumes monolayer adsorption onto a homogeneous surface with finite identical sites. The linear form of the Langmuir equation is given as:

$$\frac{C_e}{q_e} = \frac{1}{q_{max}K_L} + \frac{C_e}{q_{max}} \quad (4)$$

where C_e = equilibrium concentration of adsorbate in solution (mg/L); q_e = amount of adsorbate adsorbed at equilibrium (mg/g); q_{max} = maximum monolayer adsorption capacity (mg/g); K_L = Langmuir adsorption constant related to affinity of binding sites (L/mg).

Freundlich isotherm model. The Freundlich isotherm describes adsorption on heterogeneous surfaces and multilayer adsorption. The linear form is expressed as:

$$lnq_e = lnK_F + \frac{1}{n}lnC_e \quad (5)$$

where K_F = Freundlich constant indicative of adsorption capacity ((mg/g)(L/mg)$^{1/n}$) and n = adsorption intensity (dimensionless), indicating favorability of adsorption.

Pseudo-first-order (PFO) model. The pseudo-first-order kinetic model assumes that the rate of occupation of adsorption sites is proportional to the number of unoccupied sites. The linear form is expressed as:

$$ln(q_e - q_t) = lnq_e - k_1 t \quad (6)$$

where q_t = amount of adsorbate adsorbed at time t (mg/g); k_1 = pseudo-first-order rate constant (min^{-1}); t = contact time (min).

Pseudo-second-order (PSO) model. The pseudo-second-order kinetic model assumes that adsorption follows chemisorption involving valence forces through sharing or exchange of electrons. The linear form is given as:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \quad (7)$$

where k_2 = pseudo-second-order rate constant (g mg^{-1} min^{-1}).

Microbial Enumeration

Microbial analysis of the water samples was conducted to determine Total Coliform (TC) and *Escherichia coli* counts before and after treatment with cassava peel adsorbent, following standard microbiological procedures. The enumeration was carried out using the membrane filtration technique. A measured volume (100 mL) of each water sample was filtered through a sterile membrane filter of 0.45 µm pore size.

The membrane filters were aseptically transferred onto selective culture media. For Total Coliform determination, filters were placed on coliform-selective agar and incubated at 37°C for 24 hours. For *Escherichia coli*, selective media specific for fecal coliforms were used, and incubation was conducted at 44–45°C for 24 hours. After incubation, visible colonies were counted and expressed as colony-forming units per 100 mL (CFU/100 mL). Colony morphology and distinct characteristics were used to differentiate *E. coli* from other coliform bacteria. All analyses were performed in duplicates, and mean values were recorded.

Adsorbent Dosage (Fixed Volume and Experimental Conditions)

Following the method described by Ojo and Adewuyi [21], different dosages of cassava peel adsorbent were applied to evaluate bacteriological removal efficiency. Measured quantities of the adsorbent, including 0.5 g, 1.0 g, 1.5 g, 2.0 g, and 2.5 g, were added to a fixed volume of 100 mL of contaminated water samples in sterile 250 mL conical flasks under batch experimental conditions. The experiments were conducted at ambient laboratory temperature (25 ± 2°C) with continuous agitation using a mechanical shaker at 120 rpm to ensure proper mixing and contact between the adsorbent and microbial contaminants. The contact time was maintained at predetermined intervals during the adsorption process before microbial analysis was carried out.

Calculation of Microbial Removal Efficiency

The removal efficiency of Total Coliform and *Escherichia coli* by cassava peel adsorbent was calculated using initial and final microbial concentrations according to standard adsorption evaluation methods [21]:

$$\%Removal = \frac{C_o - C_e}{C_o} \times 100 \qquad (8)$$

where C_o = initial concentration of microorganisms (CFU/100 mL) and C_e = final concentration after treatment (CFU/100 mL). This equation was used to determine the percentage reduction in microbial load at different adsorbent dosages.

3. Results

Removal Efficiency of Heavy Metals Using Acid-Modified Cassava Peel

Figures 1–4 show the removal efficiency of cadmium (Cd), lead (Pb), chromium (Cr), and nickel (Ni) under varying experimental conditions of adsorbent dosage, contact time, pH, and initial concentration.

The removal efficiency of all metals increased with increasing adsorbent dosage and contact time. Maximum removal efficiencies were observed at the highest dosage (2.5 g) and longest contact time (120 minutes) for all metals. With respect to pH, removal efficiency increased with increasing pH up to an optimum value, after which a decline was observed. Maximum removal efficiencies for Cd, Pb, Cr, and Ni were recorded at pH 7.

In contrast, removal efficiency decreased with increasing initial metal concentration across all metals studied. Higher efficiencies were observed at lower concentrations (10 mg/L), while reduced efficiencies were recorded at higher concentrations (50 mg/L).

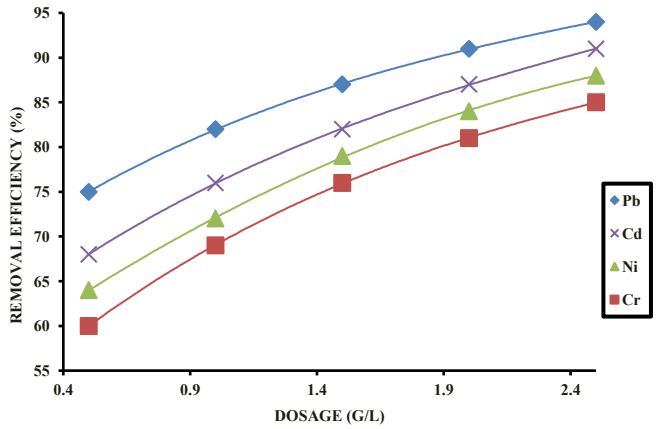


Fig. 1. Removal Efficiency against Adsorbent Dosage

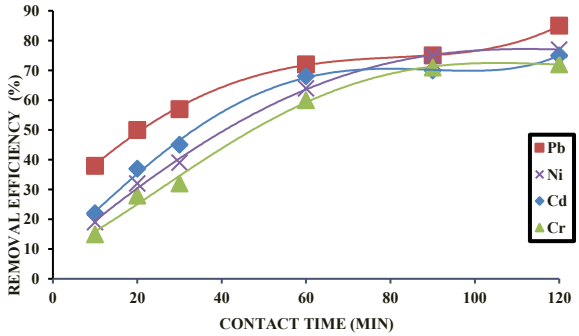


Fig. 2. Removal Efficiency against Contact Time.

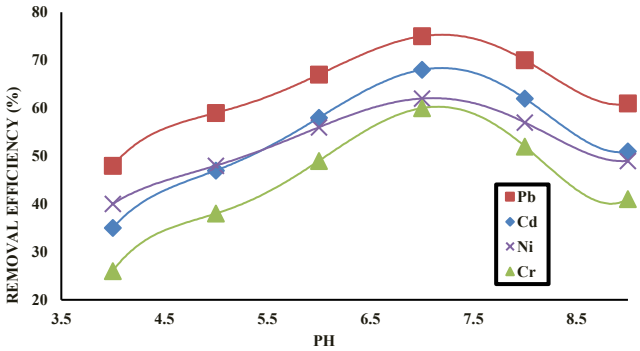


Fig. 3. Removal Efficiency against pH.

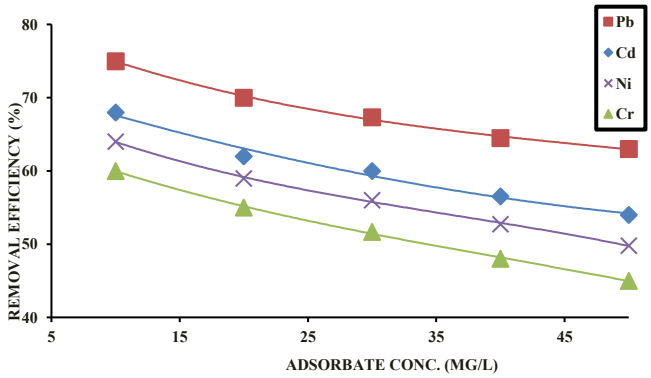


Fig. 4. Removal Efficiency against Adsorbate Concentration.

Adsorption Isotherm Studies

Langmuir Adsorption Isotherm

Figures 5 show the Langmuir adsorption isotherm plots for the removal of Cd, Pb, Cr, and Ni using cassava peel adsorbent, respectively. The plots present the relationship between equilibrium concentration (C_e) and C_e/q_e for the respective heavy metals.

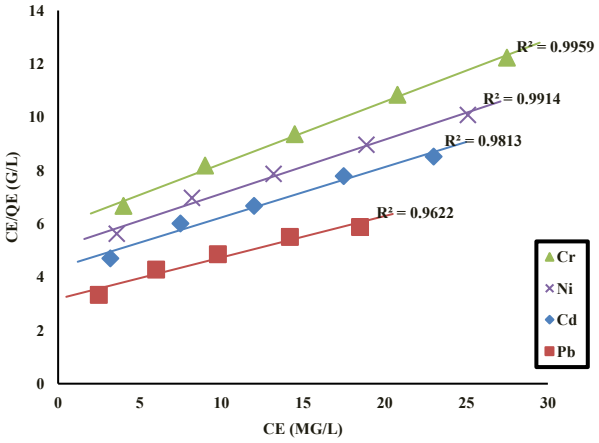


Fig. 5. Langmuir isotherm for Cadmium (Cd) adsorption.

3.2.2 Freundlich Adsorption Isotherm

Figures 6 show the Freundlich adsorption isotherm plots for the removal of Cd, Pb, Cr, and Ni using cassava peel adsorbent, respectively. The plots present the relationship between ln(q_e (mg g^{-1})) and ln C_e for the respective heavy metals.

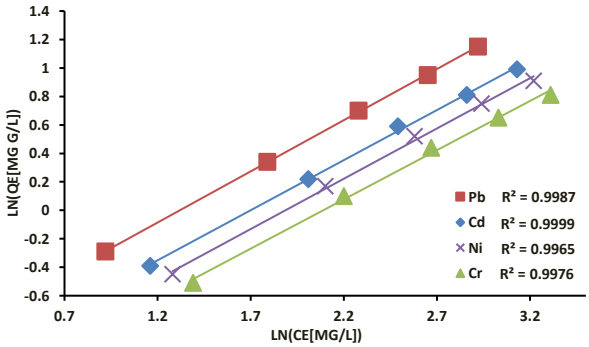


Fig. 6. Freundlich Adsorption Isotherm for Cd, Pb, Cr and Ni

3.2.3 Comparison of Isotherm Models

Table 1 presents the comparison of Langmuir and Freundlich isotherm models for the adsorption of Cd, Pb, Cr, and Ni onto cassava peel adsorbent. The Freundlich model showed higher correlation coefficients for Cd (R^2 = 0.999), Pb (R^2 = 0.999), Cr (R^2 = 0.997), and Ni (R^2 = 0.998) compared to the Langmuir model values of 0.982, 0.962, 0.996, and 0.992 respectively. The Langmuir maximum adsorption capacities (q_{max}) were 5.3070 mg/g for Cd, 6.4395 mg/g for Pb, 4.2868 mg/g for Cr, and 4.9408 mg/g for Ni. The Freundlich constants (K_F) and adsorption intensity (n) were 0.3035 and 1.4237 for Cd, 0.3894 and 1.3965 for Pb, 0.2362 and 1.4488 for Cr, and 0.2639 and 1.4172 for Ni respectively. The results indicate that the Freundlich isotherm provided the best fit for all the heavy metals studied.

Table 1. Comparison of Langmuir and Freundlich isotherm models for heavy metal adsorption onto cassava peel adsorbent.

Metal	Model	Parameters	R^2	Best fit
Cd	Langmuir	q_{max} = 5.3070, K_L = 0.0433	0.982	
	Freundlich	K_F = 0.3035, n = 1.4237	0.999	Freundlich
Pb	Langmuir	q_{max} = 6.4395, K_L = 0.0487	0.962	
	Freundlich	K_F = 0.3894, n = 1.3965	0.999	Freundlich
Cr	Langmuir	q_{max} = 4.2868, K_L = 0.0394	0.996	
	Freundlich	K_F = 0.2362, n = 1.4488	0.997	Freundlich
Ni	Langmuir	q_{max} = 4.9408, K_L = 0.0396	0.992	
	Freundlich	K_F = 0.2639, n = 1.4172	0.997	Freundlich

3.3 Adsorption Kinetics Studies

3.3.1 Pseudo-First-Order Kinetic Model

Figures 7 show the pseudo-first-order kinetic plots for the adsorption of Cd, Pb, Cr, and Ni using cassava peel adsorbent, respectively. The plots present the relationship between $\ln(q_e - q_t)$ and time (t) for the respective heavy metals.

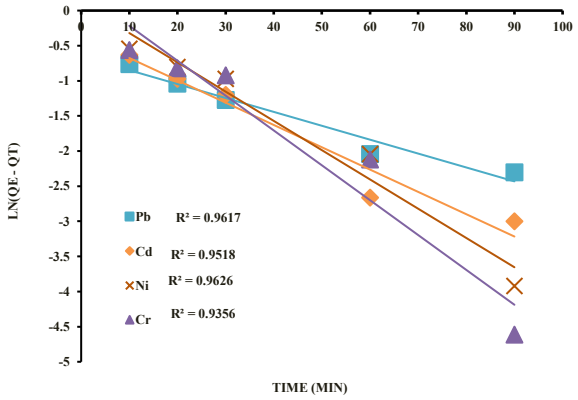


Fig. 7. Pseudo-First Order Kinetic Model for the Adsorption of Cd, Pb, Cr and Ni

3.3.2 Pseudo-Second-Order Kinetic Model

Figures 8 shows the pseudo-second-order kinetic plots for the adsorption of Cd, Pb, Cr, and Ni using cassava peel adsorbent, respectively. The plots present the relationship between t/q_t and time (t) for the respective heavy metals.

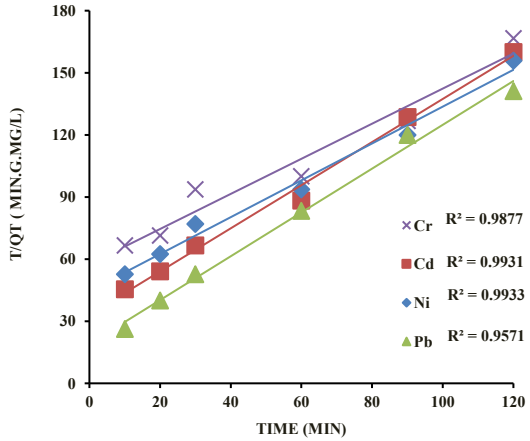


Figure 8: Pseudo-Second Order Kinetic Model for the Adsorption of Cd, Pb, Cr and Ni

3.3.3 Kinetic Model Comparison

Table 2 presents the comparison of pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic models for the adsorption of Cd, Pb, Cr, and Ni. The PSO model exhibited higher correlation coefficients for Cd ($R^2 = 0.9931$), Pb ($R^2 = 0.9571$), and Ni ($R^2 = 0.9933$) compared to the PFO model, indicating a better fit for these metals. Overall, the PSO kinetic model best described the adsorption behaviour of Cd, Pb, and Ni, suggesting chemisorption as the dominant mechanism.

Table 2. Comparison of pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic parameters for heavy metal adsorption.

Parameter	Cd	Pb	Cr	Ni
PFO: k_1 (min^{-1})	0.0317	0.0198	0.0496	0.0416
PFO: q_e calc. (mg/g)	0.697	0.52	1.319	1.098
PFO: R^2	0.9515	0.9615	0.9355	0.9626
q_e exp. (mg/g)	0.75	0.85	0.72	0.77
PSO: k_2 (g mg^{-1} min^{-1})	0.0326	0.0588	0.00826	0.0177
PSO: q_e calc. (mg/g)	0.9602	0.9449	1.401	1.124
PSO: R^2	0.9931	0.9571	0.9877	0.9933

3.4 Microbial Removal Efficiency

Table 3 presents the reduction of Total Coliform (TC) and *Escherichia coli* following treatment with cassava peel adsorbent at varying dosages. The initial microbial load for the untreated

sample was 2.40 × 10^3 CFU/100 mL for Total Coliform and 1.00 × 10^3 CFU/100 mL for *E. coli*. No reduction was observed in the control sample (0.0 g), as expected.

At an adsorbent dosage of 0.5 g, Total Coliform decreased to 9.50 × 10^2 CFU/100 mL, corresponding to 60.42% removal, while *E. coli* reduced to 3.80 × 10^2 CFU/100 mL, representing 62.00% removal. Increasing the dosage to 1.0 g resulted in further reduction, with Total Coliform recorded at 6.80 × 10^2 CFU/100 mL (71.67%) and *E. coli* at 2.60 × 10^2 CFU/100 mL (74.00%). At 1.5 g dosage, Total Coliform was reduced to 4.20 × 10^2 CFU/100 mL (82.50%), while *E. coli* decreased to 1.60 × 10^2 CFU/100 mL (84.00%). A more pronounced reduction was observed at 2.0 g, where Total Coliform reached 2.30 × 10^2 CFU/100 mL (90.42%) and *E. coli* decreased to 9.00 × 10^1 CFU/100 mL (91.00%).

The highest removal efficiency was recorded at 2.5 g dosage, with Total Coliform reduced to 1.10 × 10^2 CFU/100 mL (95.42%) and *E. coli* to 4.50 × 10^1 CFU/100 mL (95.50%). Overall, microbial reduction increased progressively with increasing adsorbent dosage.

Table 3. Reduction of Total Coliform and *Escherichia coli* using cassava peel adsorbent.

Dosage (g)	Final TC (CFU/100 mL)	TC removal (%)	Final *E. coli* (CFU/100 mL)	*E. coli* removal (%)
0.0 (control)	2.40 × 10^3	0.00	1.00 × 10^3	0.00
0.5	9.50 × 10^2	60.42	3.80 × 10^2	62.00
1.0	6.80 × 10^2	71.67	2.60 × 10^2	74.00
1.5	4.20 × 10^2	82.50	1.60 × 10^2	84.00
2.0	2.30 × 10^2	90.42	9.00 × 10^1	91.00
2.5	1.10 × 10^2	95.42	4.50 × 10^1	95.50

Initial microbial load (all treatments): Total Coliform (TC) 2.40 × 10^3 CFU/100 mL; *E. coli* 1.00 × 10^3 CFU/100 mL.

4. Discussion

Maximum removal of Cd, Pb, Cr and Ni by the acid-modified cassava peel occurred at pH 7, reflecting the role of pH in governing both the adsorbent's surface charge and the speciation of the metal ions. At lower pH (4–5), protonation of functional groups such as -OH and -COOH makes the surface positively charged, and H^+ ions compete with the metal cations (Cd^{2+}, Pb^{2+}, Cr^{3+}, Ni^{2+}) for binding sites. As the pH approaches neutral, the surface becomes more negatively charged and electrostatic attraction to the cations increases. Removal fell at pH 8 and 9 because the metals precipitate as hydroxides, e.g. $Cd(OH)_2$ and $Pb(OH)_2$, so less free cation is available and the real adsorption is masked [22]. Maduelosi et al. [23] and Karimi-Darvanjooghi et al. [25] found optima at pH 4 and Aliyu et al. [24] at pH 2. The higher optimum here (pH 7) may be due to the functional groups introduced by the modification or to the buffering property of the acid-modified peel.

Removal efficiency increased progressively with adsorbent dosage because more adsorption sites become available, a trend also reported by Aliyu et al. [24] and Sulaiman et al. [26]. Maduelosi et al. [23] observed a later decline in capacity due to surface saturation or particle aggregation. No marked decline appeared here; the plateau at higher doses suggests equilibrium was likely approached.

Removal also increased with contact time, with maximum values at 120 minutes. Metal cations diffuse from the bulk solution and progressively occupy free active sites until the sites become saturated and the rate becomes constant. Olaoye et al. [27] and Schwantes et al. [28] reported shorter equilibrium times (60 and about 40 minutes). The longer time here may be due to the heterogeneous pore structure of the peel, which slows diffusion to inner binding sites.

Percentage removal fell as initial concentration rose from 10 to 50 mg/L, because the number of available sites is limited relative to the metal load. However, q_e increased, since higher initial concentrations provide a greater driving force for mass transfer. This agrees with Tejada-Tovar et al. [29] and Mutiara et al. [30].

The Freundlich model gave higher correlation coefficients than the Langmuir model for all four metals: Cd (0.999 vs 0.982), Pb (0.999 vs 0.962), Cr (0.997 vs 0.996) and Ni (0.998 vs 0.992). This suggests adsorption on a heterogeneous surface with multilayer coverage and varying binding energies. All n values were greater than 1 (Cd 1.4237, Pb 1.3965, Cr 1.4488, Ni 1.4172), indicating favourable adsorption. The Freundlich K_F values gave the order Pb (0.3894) > Cd (0.3035) > Ni (0.2639) > Cr (0.2362), reflecting the greater affinity of the modified peel for Pb. The Langmuir q_max values (Pb 6.4395, Cd 5.3070, Ni 4.9408, Cr 4.2868 mg/g) followed the same order. Schwantes et al. [31] reported higher capacities (42.46 mg/g for Pb and 19.54 mg/g for Cd) with NaOH-modified cassava peel, possibly due to the NaOH modification. The Freundlich fit agrees with Sulaiman et al. [26] and Tejada-Tovar et al. [29]. The kinetic results showed that the pseudo-second-order (PSO) model provided a better fit for Cd, Cr and Ni, with R^2 values of 0.9931, 0.9877 and 0.9933, respectively, compared with 0.9515, 0.9355 and 0.9626 obtained from the pseudo-first-order (PFO) model. In contrast, Pb showed a slightly better fit to the PFO model (R^2 = 0.9615) than to the PSO model (R^2 = 0.9571). The better performance of the PSO model for Cd, Cr and Ni suggests that the adsorption kinetics of these metals may involve interactions between the adsorbate ions and active sites on the adsorbent surface, potentially including electron sharing or exchange with functional groups such as –OH, –COOH and C=O. However, because the adsorbent was not characterized in the present study, these proposed interactions should be regarded as possible mechanisms rather than experimentally confirmed surface reactions.

The calculated equilibrium adsorption capacities (q_e,calc) also showed some agreement with the experimentally determined values (q_e,exp). For example, the experimental and PSO-calculated q_e values were 0.75 and 0.9602 mg/g for Cd, 0.85 and 0.9449 mg/g for Pb, 0.72 and 1.401 mg/g for Cr, and 0.77 and 1.124 mg/g for Ni, respectively. The relatively close agreement observed for Pb, despite its slightly higher PFO R^2 value, indicates that both kinetic models provide reasonable representations of the adsorption process. The stronger PSO fits obtained for Cd, Cr and Ni are consistent with previous findings reported for cassava-peel-based adsorbents by Kosasih et al. [32].

4.4 Microbial removal

Total Coliform (TC) and E. coli removal increased progressively with dosage, from 60.42% (TC) and 62% (E. coli) at 0.5 g to 95.42% and 95.50% at 2.5 g (1.10×10^2 and 4.50×10^1 CFU/100 mL, from initial loads of 2.40×10^3 and 1.00×10^3 CFU/100 mL). No reduction occurred in the control (0.0 g), confirming that the adsorbent was responsible. The rise reflects the increasing number of adsorption sites with adsorbent mass, and the slowing between 2.0 and 2.5 g suggests saturation was being approached. This pattern aligns with Ojo and Adewuyi [21], who obtained about 96% E. coli and 93% total coliform removal with sawdust activated carbon at 15 g and 120 minutes, supporting cassava peel as a competitive alternative to more intensively processed adsorbents. He et al. [33] likewise found E. coli removal rising with PEI-BC dosage and then stabilizing beyond 2.0 g/L, attributed to particle aggregation, active site

overlap or blockage, and electrostatic repulsion. The deceleration seen here is consistent with that explanation

Conclusion

Findings from this research show that acid-modified cassava peel is a low-cost adsorbent that can remove heavy metals (Cd, Pb, Cr, Ni) as well as bacteria (Total Coliform and *E. coli*) from contaminated water. The adsorption of heavy metals was significantly affected by pH, dosage, contact time, and initial concentration. The optimal conditions were at pH 7, maximum dosage, 120 minutes of contact time and lower initial concentrations. The equilibrium data confirmed to best fit the Freundlich isotherm model which indicates heterogeneous multilayer adsorption. The rate behaviour for Cd, Pb and Ni was best described by the pseudo-second-order kinetic model which exhibited chemisorption. As the dosage of the adsorbent increases, the removal efficiency of microbial also increases. Removal efficiency achieved was approximately 95% at 2.5 g/100 mL. But residual counts show that further treatment is required to achieve WHO standards for potable water. The current results are consistent with the information available on the topic and are helpful in increasing literature that can support the use of waste-based adsorbents as easily accessible water treatment.

Pilot-scale and real-field applications should be conducted to evaluate the performance of cassava peel adsorbent in continuous flow systems and real wastewater environments. Combination of cassava peel adsorbent with other treatment methods (e.g., filtration or disinfection) is recommended to achieve complete water purification, and additional research should explore regeneration and reuse potential of the adsorbent to improve its economic feasibility and long-term application.

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