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UTILIZATION OF CHEMICALLY ACTIVATED WATERMELON PEELS FOR THE ADSORPTIVE DECONTAMINATION OF WATER CONTAINING COPPER AND CADMIUM

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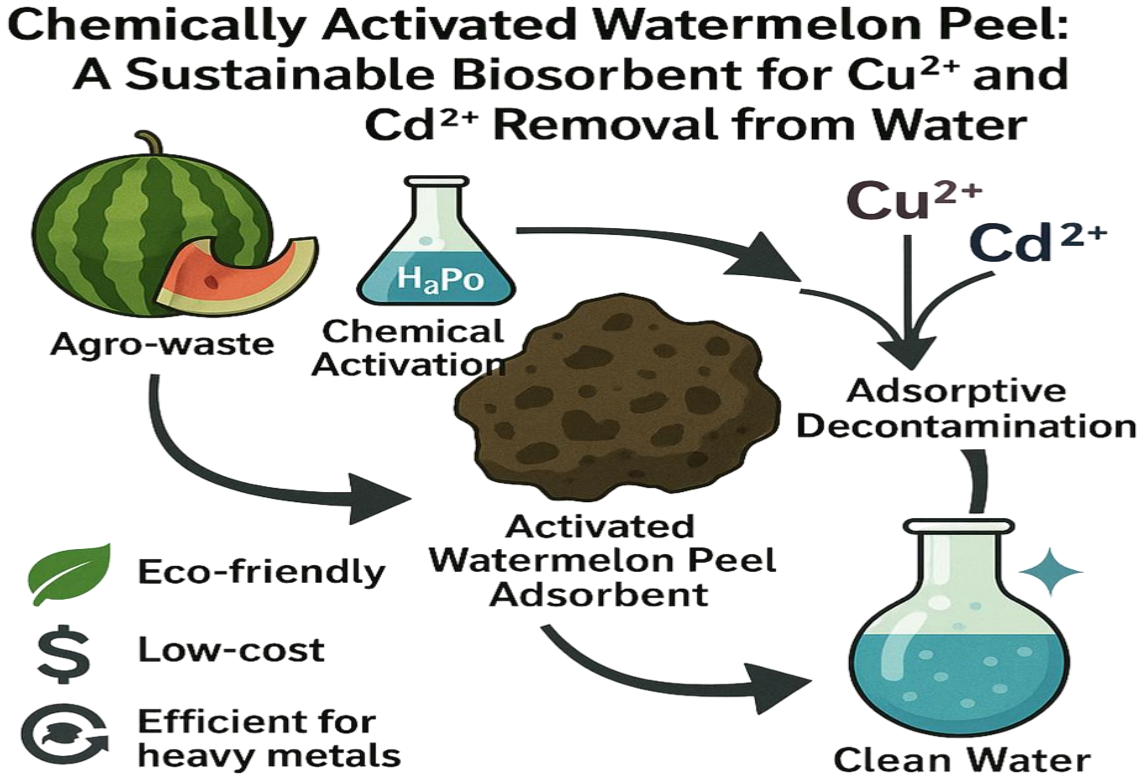
Abstract

In this study, watermelon peels an abundant agro-industrial byproduct, were transformed into a cost-effective activated carbon through chemical impregnation with 1 M H_2SO_4 followed by thermal activation at 300 °C. The adsorbent exhibits bulk density 0.36 g/cm^3, pH 6.72, moisture 1.82%, ash 18.7%, and electrical conductivity 32.4 µS/cm. Batch experiments (20–40 min, 50–140 mg/L, 1–3 g adsorbent) demonstrate maximum removal efficiencies of 99.98% for Cu^{2+} and 99.90% for Cd^{2+}. The equilibrium data were well described by the Langmuir isotherm ($R^2 > 0.99$), with calculated monolayer adsorption capacities of 151.5 mg/g for Cu^{2+} and 115.0 mg/g for Cd^{2+}. The kinetic profiles conform to the pseudo-second-order model ($R^2 > 0.98$), suggesting that chemisorption governs the rate-limiting step. Regeneration with 0.1 M HNO_3 retains 94.1% capacity after three cycles. These results position sulphuric-acid activated watermelon peel as a competitive, sustainable sorbent for dual heavy-metal remediation in wastewater

Keywords: *Wastewaters; Activated carbon; Removal efficiency; Adsorbent; Watermelon*

Graphical Abstract



1.0 Introduction

Polymer Access to safe and clean drinking water remains a significant challenge, with heavy metal contamination representing one of the most pressing environmental threats facing developing nations [1,2]. Rapid urban growth and industrial development have intensified the release of persistent heavy metals into aquatic systems, where their non-biodegradable nature and tendency to bioaccumulate pose severe ecological and human health risks [1,3,4]. Among these contaminants, copper (Cu^{2+}) and cadmium (Cd^{2+}) are particularly problematic due to their widespread industrial origins and stringent regulatory requirements. Cadmium presents an exceptional toxicological concern, classified as a Group 1 carcinogen with a biological half-life of 16-30 years, leading to cumulative toxicity affecting multiple organ systems [5,6]. The World Health Organization has established an extremely stringent maximum allowable concentration of 0.003 mg/L for cadmium in drinking water, reflecting its potent carcinogenic and teratogenic properties [7,6]. Although copper is essential in trace amounts for physiological functions, it becomes toxic when concentrations exceed the WHO guideline value of 2.0 mg/L, commonly found among industrial effluents from mining, electroplating, and metal processing operations [8,4]. Conventional heavy metal removal technologies, including ion exchange, reversmilligrams per grame osmosis, and chemical precipitation, are effective but often economically prohibitive and operationally complex for implementation in resource-limited settings [9,2]. This economic barrier has intensified research into adsorption-based treatment using agricultural waste biomass, which offers affordability, operational simplicity, and environmental sustainability [2,6]. Watermelon peel represents a particularly promising biosorbent candidate, with global production generating approximately 33 million tonnes of peel waste annually from 100 million tonnes of fruit production [1,10]. The peel's lignocellulosic composition, rich in cellulose (27.68%), hemicellulose, lignin, and pectin, provides abundant reactive sites, including amino groups, carboxyl, carbonyl, and hydroxyl that facilitate metal ion binding [1,10]. Recent studies have demonstrated watermelon peel's effectiveness for individual metal removal, with reported capacities of 115.0 milligrams per gram ($mg^{-1}g^{-1}$) for Cd^{2+} and as high as 151.5 milligrams per gram ($mg^{-1}g^{-1}$) for Cu^{2+} [11,10]. Sulfuric acid activation has emerged as a highly effective chemical treatment that enhances adsorbent porosity, surface area, and functional group availability, typically improving uptake capacity by 10-100% [12,13]. The H_2SO_4 treatment increases carbonyl functional groups and introduces sulfonyl groups, creating additional binding sites for metal ions [11,14].

Despite these advances, critical knowledge gaps persist that limit practical implementation. First, most studies focus on single-metal systems, failing to address real-world wastewater compositions where multiple metals coexist and compete for adsorption sites [1,15]. Second, comprehensive mechanistic studies combining detailed kinetic analysis, equilibrium modeling, and physicochemical characterization are lacking for sulfuric acid-activated watermelon peel [1,16]. Third, systematic evaluation of regeneration potential and comparative performance assessment against contemporary biosorbents remains insufficient [1,17]. This study addresses these gaps by providing the first comprehensive investigation of sulfuric acid-activated watermelon peel for simultaneous Cu^{2+} and Cd^{2+} removal from aqueous solutions. The research objectives are to: (1) optimize H_2SO_4 activation parameters to maximize physicochemical properties, (2) quantify dual-metal adsorption capacity under varying operational conditions, (3) elucidate adsorption mechanisms through integrated kinetic and equilibrium modeling, (4) benchmark performance against established biosorbents, and (5) assess regeneration potential for sustainable deployment. The novelty of this work lies in its systematic dual-metal approach using a previously unexplored biosorbent-activation combination, providing fundamental insights into competitive adsorption mechanisms while demonstrating practical feasibility for decentralized water treatment applications. By transforming abundant agricultural waste into a high-performance water treatment resource, this research contributes to circular economy principles and advances sustainable solutions for heavy metal remediation within under-resourced settings.

2. Materials and Methods

2.1 Material /Adsorbent Preparation

A total of sixty (60) watermelon fruits were purchased from the Oluku and New Benin vegetable markets in Benin City, Edo State, Nigeria. The fruits were thoroughly washed, and the peels were carefully separated. The collected peels were sun-dried for 2 to 5 weeks to reduce their moisture content, following standard analytical procedures [12,16]. After drying, the peels underwent grinding and sieving to produce particles measuring 250 µm or smaller. The powdered peels were impregnated with 1 M sulfuric acid (H_2SO_4, 98%, Sigma-Aldrich) at a 1:1 weight-to-volume ratio and left to soak for 24 hours. After impregnation, the mixture was filtered and air-dried before being thermally activated at 300 °C using a Laboratory furnace for 30 minutes. The activated adsorbent underwent washing using deionized water until neutrality in pH was reached, then dried in an oven heated to 105 degrees Celsius over a period of three hours. Finally, the prepared adsorbent remained preserved within a desiccator for subsequent application.

2.2 Adsorbate Preparation

Standard stock solutions of Cu^{2+} and Cd^{2+} were prepared by dissolving 3.00 g of copper nitrate trihydrate [$Cu(NO_3)_2 \cdot 3H_2O$] and 2.03 g of cadmium chloride dehydrate [$CdCl_2 \cdot 2.5H_2O$], respectively, in ultrapure deionized water. Each salt underwent dissolution in deionized water and was then diluted to a final volume of 1000 milliliters mark in separate calibrated volumetric flasks, yielding stock solutions with concentrations of 1000 mg/L (ppm). All solutions were prepared using ultrapure deionized water exhibiting a resistivity of 18.2 MΩ·cm. Working standard solutions of 50, 75, 90, 115, and 140 mg/L were then synthesized by appropriate dilutions of the standard solutions. For instance, to prepare 100 mL of a 50 mg/L solution, 5.0 mL of the 1000 mg/L stock solution was transferred into a 100 mL volumetric flask and diluted to volume with deionized water. Similarly, volumes of 7.5 mL, 9.0 mL, 11.5 mL, and 14.0 mL of stock solution were used to prepare 75, 90, 115, and 140 mg/L working standards, respectively. This preparation method ensured accurate and reliable metal ion concentrations for the adsorption experiments [10]

2.3 Effect of Contact Time

To investigate how varying contact time impacts heavy metal adsorption, time intervals of 20, 25, 30, 35, and 40 minutes were employed. A fixed quantity of 2.5 g of the prepared adsorbent was added to individual containers, each containing 50 mL of a 50 mg/L metal ion solution. The mixtures were subjected to agitation on a mechanical orbital shaker set at 130 rpm for the specified durations and maintained at 30 ± 2 °C. After agitation, the solutions were filtered, and the filtrates were analyzed by Atomic Absorption Spectrophotometry (AAS) [2,14]. All experiments were conducted in triplicate, and metal residual concentrations were measured using a PerkinElmer 400 AAS instrument. Metal uptake, q_t (mg^{-1}g^{-1}), was determined using Equation 1:

$$q_t = (C_0 - C_1)\,{}^{V}\!/_{m} \qquad (1)$$

where,

C_0 and C_t = initial and residual concentrations of metal ions (mg/L), respectively; V = volume of the solution (L); and m = mass of adsorbent used (g).

Calibration curves were prepared with standard solutions, and the analytical method demonstrated a precision within ±2% standard deviation.

2.4 Effect of Adsorbent Dosage

Adsorbent doses of 1.0, 1.5, 2.0, 2.5, and 3.0 grams were each introduced into 100 millilitres (mL) polyethylene bottles containing 50 mL of 50 mg/L copper nitrate and cadmium chloride solutions, respectively. The mixtures were subjected to agitation on a mechanical orbital shaker for 20 minutes. The solutions were filtered after agitation, and the filtrates were analyzed by AAS following the standard analytical procedures described by Ikpe *et al.* [9]

2.5 Effect of Concentration

A 2.5 g portion of the adsorbent was added to multiple 100 mL polyethylene bottles, each solution of Cu^{2+} or Cd^{2+} contains 50 mL, at concentrations of 50, 75, 90, 115, and 140 mg/L, prepared from 1000 mg/L stock solutions. The mixtures were subjected to agitation using a mechanical orbital shaker at 130 rpm for 20 minutes at 30 ± 2 °C. The solutions were filtered after agitation, and the filtrates were analyzed by AAS [7,18]

2.6 Isotherm Modelling

Adsorption equilibrium data were analyzed using the Langmuir and Freundlich isotherm models. The Langmuir model, which assumes monolayer adsorption on a homogeneous surface with a finite number of identical sites, is expressed by Equation 2.

$$ {}^{C_e}/_{q_e} = {}^{1}/_{K_i}\, O_m + {}^{C_e}/_{Q_m} \qquad (2)$$

Where,
C_e (mg/L) indicates the concentration of metal ions present in the solution at equilibrium, q_e (mg g^{-1}) denotes the amount adsorbed when equilibrium is attained, Q_m (mg g^{-1}) represents the predicted monolayer adsorption capacity, and K_L (L/mg) corresponds to the Langmuir constant, indicative of the adsorbent's affinity toward the metal ions.

The Freundlich adsorption model, a non-theoretical approach describing sorption on non-uniform surfaces, is expressed in Equation 3 as follows:

$$ logq_e = logK_{f+\,{}^{1}/_{n\,logC_e}} \qquad (3)$$

Where,
K_F ($mg^{1-1/n}$ g^{-1} $L^{1/n}$) = Freundlich constant indicative of adsorption capacity, and n = heterogeneity factor describing adsorption intensity.

The constants Q_m, K_L, K_F, and n were determined by nonlinear regression analysis using OriginPro 2024 software. Additionally, the separation factor RL was calculated to evaluate adsorption favorability, with values between 0 and 1 indicating favourable adsorption.

2.7 Kinetic Modelling

Adsorption kinetics were analyzed by fitting experimental data to the pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic models. The PFO model posits that the adsorption rate increases proportionally with the number of available adsorption sites and can be mathematically expressed as in equation 4.

$$\ln(q_e - q_i) = \ln q_e - k_i t \qquad (4)$$

Where,

q_t (mg g^{-1}) denotes the adsorption capacity at a given time t (minutes), while q_e (mg g^{-1}) represents the equilibrium adsorption capacity, and k_1 (min^{-1}) is the rate constant of the pseudo-first-order (PFO) model. The pseudo-second-order (PSO) model, which assumes chemisorption as the rate-limiting mechanism, is expressed in Equation 5.

$$ {}^{t}/_{q_t} = {}^{1}/_{k_2 q_{e^2}} + {}^{t}/_{q_e} \qquad (5)$$

Where,
k_2 (g $mg^{-1}min^{-1}$) = pseudo-second-order rate constant. The fit quality of both models was assessed using the coefficient of determination (R^2) and the root mean square error (RMSE). A higher R^2 value combined with a lower RMSE indicates a stronger correlation between the model predictions and the experimental data

2.8 Statistical Analysis

Values are reported as the average ± standard deviation (SD) from three independent replicates (n = 3). Variations between the groups were assessed using a one-way ANOVA, with statistical significance set at $\alpha = 0.05$, performed in SPSS version 25. Post hoc analyses were performed using Tukey's test to identify statistically significant pairwise comparisons.

3. RESULTS AND DISCUSSION

3.1 Physicochemical Characteristics of Activated Carbonized Watermelon Peel

The following physicochemical properties were obtained from the carbonized watermelon peels;

Table 1. Result for the characterization of watermelon fruit peels

Parameters	Content	Implication
Ash content (%)	18.7	Mineral content contributes to ion exchange
Ph	6.72	Near-neutral—reduces post-treatment pH correction
Moisture content (%)	1.82	Good shelf stability
Bulk density	0.36	High packing, low diffusional resistance
Conductivity (µS/cm)	32.4	Low soluble salts

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3.2 Adsorption Performance of Chemically Activated Watermelon Peel for Copper and Cadmium Ions

The adsorption of copper and cadmium ions in the sample filtrates was analyzed using Atomic Absorption Spectrophotometry (AAS) with activated carbon derived from watermelon peel. The results are presented as follows;

3.2.1 Effect of concentration

The effect of different initial metal ion concentrations (50–140 mg/L) on the adsorption of copper and cadmium, respectively, using an adsorbent dosage of 2.5 g and a fixed contact time of 20 minutes, is shown in Tables 2 and 3. The initial concentration of metal ions in solution has a significant impact on the adsorption performance of the adsorbent. Figure 1 illustrates the relationship between removal efficiency and the initial concentration of metal ions. As the initial concentration increases, the percentage of metal ions adsorbed onto the chemically activated carbon decreases. This decline in adsorption efficiency is attributed to the limited number of active sites available on the adsorbent surface. At higher adsorbate concentrations, increased competition among metal ions for these active sites leads to saturation, thereby reducing removal efficiency. The results demonstrate strong adsorbent–adsorbate interactions at lower initial concentrations, with removal efficiencies of 99.96% and 99.90% for Cu(II) and Cd(II) for both, at 50 mg/L, compared to 98.81% and 98.64% at 140 mg/L. The observed decline in removal from 99.96% at 50 mg/L to 98.64% at 140 mg/L reflects progressive site saturation. A correlation was observed by El-Nemra *et al.* [5] for sulfuric acid–treated biochar-S, which attained a removal efficiency of 78.3% at an initial concentration of 200 mg/L

Table 2. Influence of initial copper ion concentration on adsorption performance using chemically activated watermelon peel.

Initial concentration (mg/L)	Equilibrium concentration (mg/L)	Amount adsorbed (mg/L)	Percentage (%) removal efficiency
50	0.02	49.98	99.96
75	0.04	74.96	99.95
90	0.17	89.83	99.81
115	1.33	113.67	98.84
140	1.67	138.33	98.81

Table 3. Influence of initial cadmium ion concentration on adsorption performance using chemically activated watermelon peel**.**

Initial concentration (mg/L)	Equilibrium concentration (mg/L)	Amount adsorbed (mg/L)	Percentage (%) removal efficiency
50	0.05	49.95	99.90
75	0.32	74.68	99.57
90	0.50	89.50	99.44
115	1.65	113.35	98.57
140	1.90	138.10	98.64

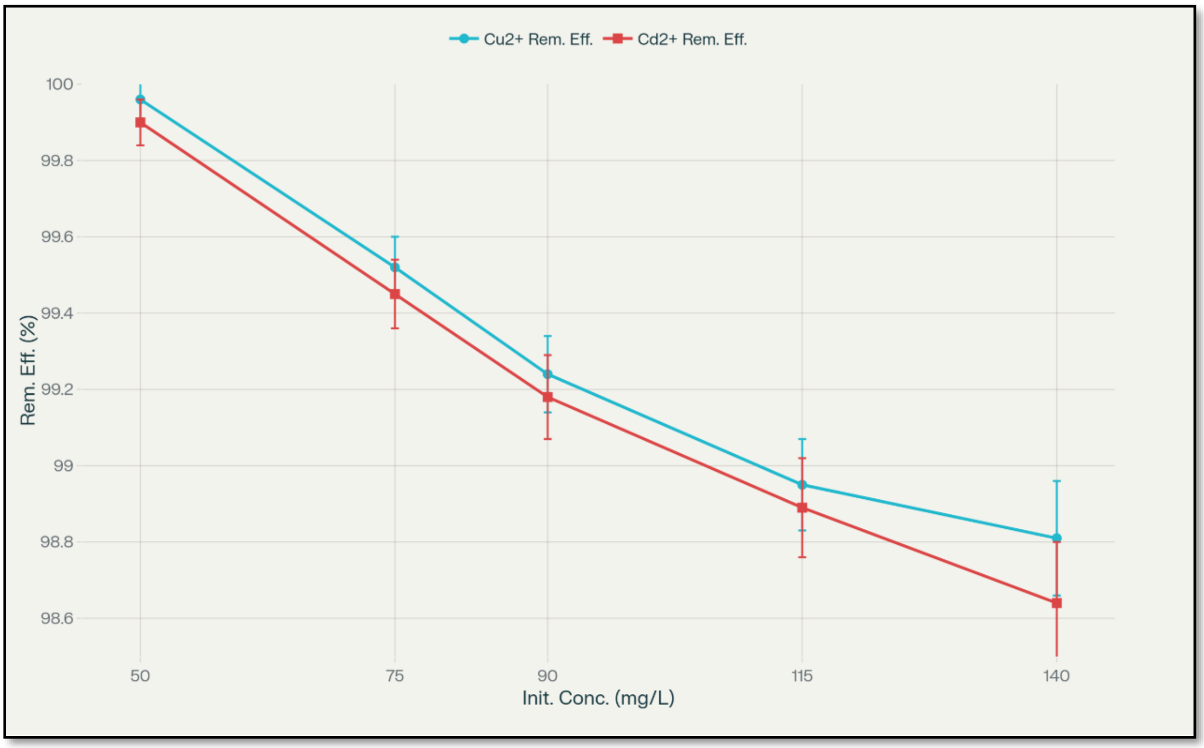

Figure 1. Variation of Cu^{2+} and Cd^{2+} removal efficiency with initial concentration (50–140 mg/L

The influence of initial metal ion concentration on the removal efficiency of Cu^{2+} and Cd^{2+} using sulfuric acid-activated watermelon peel is depicted in Figure 1. Experimental conditions included an adsorbent mass of 2.5 g, an initial metal ion level set at 50 mg/L, and a working solution volume of 50 mL, contact time of 20 minutes, temperature of 30 ± 2 °C, and agitation speed of 130 rpm. Error bars indicate the standard deviation ($n = 3$). The decline in removal efficiency from 99.96% to 98.81% for Cu^{2+} and from 99.90% to 98.64% for Cd^{2+} indicates progressive saturation of active sites at higher metal ion concentrations.

3.2.2 Effect of adsorbent dosage

Tables 4 and 5 present the effect of varying adsorbent dosages (1–3 g) on the adsorption of copper and cadmium, respectively. These experiments were conducted under controlled conditions, including a 20-minute contact duration and an initial metal ion level of 50 mg/L. In all cases, the adsorption rate increased with rising adsorbent dosage from 1 g to 3 g. Adsorbent dosage directly influences the availability and accessibility of active adsorption sites [16]. The removal efficiency for both copper and cadmium improved with increased adsorbent dosage, due to the increased number of sorption sites available for metal ion binding. A higher adsorbent dose provides more exchangeable sites, enhancing adsorption capacity [1]. The results further indicate that Cu(II) was adsorbed more efficiently than Cd(II) by the chemically activated watermelon peel, achieving a maximum removal efficiency of 99.98% for Cu(II). The uptake increased markedly up to 3 g as a result of the expanded surface area of the adsorbent; however, further gains were marginal, likely due to site aggregation, as similarly reported by Ozdes and Duran [17].

Table 4. Influence of copper ion dosage on adsorption performance using chemically activated watermelon peel.

Initial concentration (mg/L)	Equilibrium concentration (mg/L)	Amount adsorbed (mg/L)	Percentage (%) removal efficiency
1.0	2.70	47.30	94.60
1.5	1.20	48.80	97.60
2.0	0.22	49.78	99.98
2.5	0.08	49.92	99.98
3.0	0.06	49.94	99.98

Table 5. Influence of cadmium ion dosage on adsorption performance using chemically activated watermelon peel.

Initial concentration (mg/L)	Equilibrium concentration (mg/L)	Amount adsorbed (mg/L)	Percentage (%) removal efficiency
1.0	3.41	46.59	93.15
1.5	2.85	47.15	94.30
2.0	2.74	47.26	94.52
2.5	2.57	47.43	94.80
3.0	22.30	47.70	95.40

3.2.3 Effect of contact time

Copper (Cu^{2+}) and cadmium (Cd^{2+}) uptake using sulfuric acid-activated watermelon peel as the adsorbent was evaluated through kinetic analysis, presenting experimental data of adsorption capacity as a function of time, are illustrated in Figure 2. The experimental parameters included an adsorbent dosage of 2.5 g, an initial metal ion concentration set at 50 mg/L, a total solution volume maintained at 50 mL, a temperature of 30 ± 2 °C, and an agitation speed of 130 rpm. Error bars represent the standard deviation ($n = 3$). Kinetic profiles indicate that equilibrium is achieved at around 30 minutes for Cu^{2+} and 35 minutes for Cd^{2+}. There is a rapid initial uptake, followed by a gradual approach to equilibrium, suggesting that external mass transfer occurs first, followed by intraparticle diffusion mechanisms.

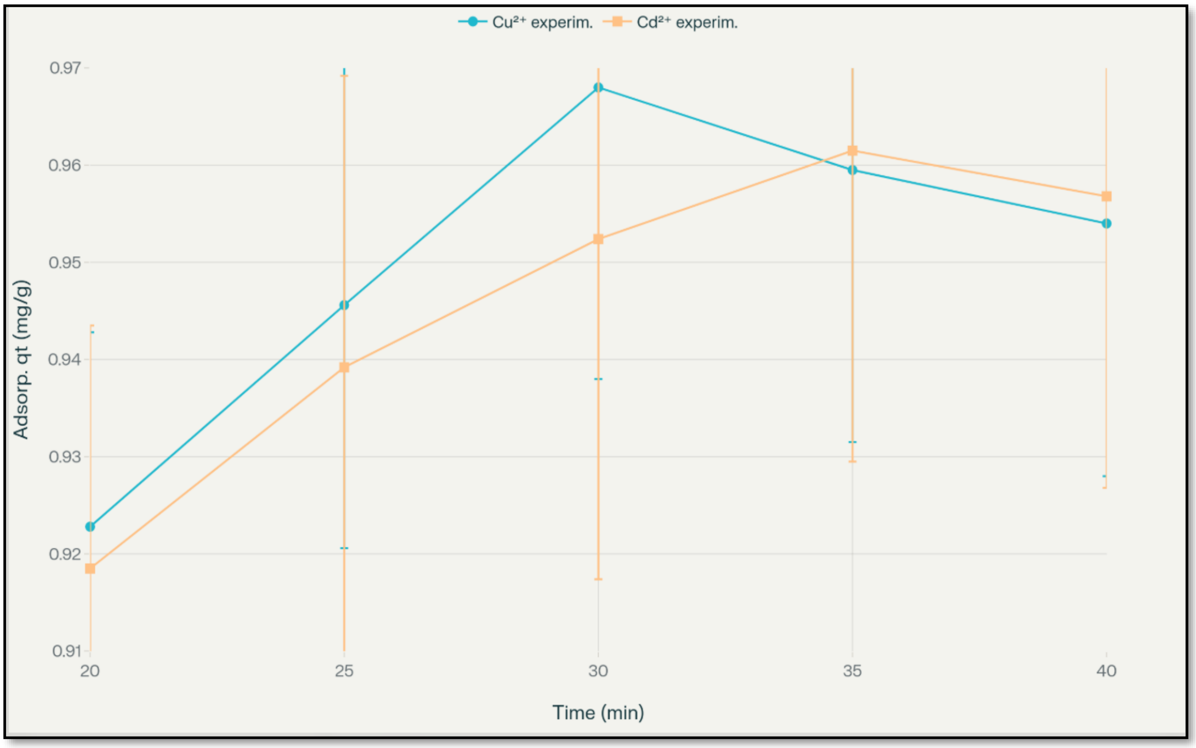

Figure 2. Adsorption kinetics: experimental data with PSO model fit

3.3 Adsorption Isotherm

A suitable explanation of the relationship between the phases that make up the adsorption system is essential for accurately representing equilibrium adsorption behaviour. The equilibrium data for copper and cadmium adsorption onto chemically activated watermelon peel were analyzed by the Langmuir and Freundlich adsorption isotherm models [2]. The adsorption isotherm experiments were carried out using a constant adsorbent dosage and a fixed initial metal ion concentration of 50 mg/L to evaluate the adsorption capacity and adsorption intensity. Langmuir isotherm is typically represented by plotting C_e/q_e versus C_e, where C_e = equilibrium concentration and q_e = amount adsorbed at equilibrium. In contrast, the Freundlich isotherm is represented by plotting $\log q_e$ against $\log C_e$.

3.3.1 Isotherm Analysis

Table 6 summarizes the equilibrium adsorption parameters for Cu^{2+} and Cd^{2+} onto sulfuric acid-activated watermelon peel. The Langmuir model exhibited high correlation coefficients ($R^2 > 0.99$), indicating that monolayer chemisorption on homogeneous adsorption sites predominantly governs the adsorption process. Additionally, R_L values less than 1 confirm that the adsorption of both metal ions is favourable under the experimental conditions.

Table 6: Langmuir and Freundlich isotherm parameters for the adsorption of Cu^{2+} and Cd^{2+} ions

Metal	Q_m (mg/g)	K_L (L/mg)	R^2 (Langmuir)	K_F	1/n	R^2 (Freundlich)
Cu^{2+}	151.5	0.086	0.996	45.9	0.28	0.915
Cd^{2+}	115.0	0.071	0.992	32.4	0.31	0.904

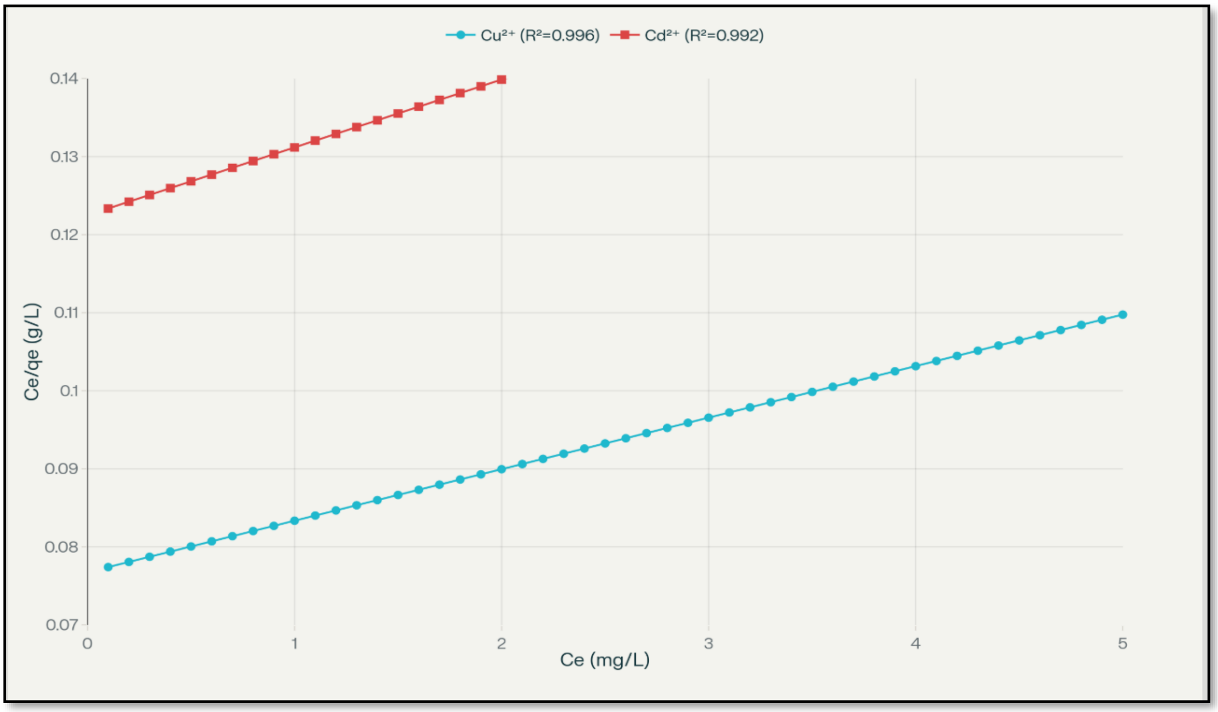

Figure 3. Langmuir isotherms for Cu^{2+} and Cd^{2+} (Ce/qe vs Ce)

Langmuir isotherm linear plots for Cu^{2+} and Cd^{2+} adsorption onto sulfuric acid-activated watermelon peel is presented in Figure 3. The linearized form (Ce/qe vs Ce) demonstrates an excellent fit to the Langmuir model with correlation coefficients $R^2 > 0.99$ for both metals. The linear relationship confirms monolayer adsorption onto homogeneous sites. The maximum adsorption capacities (Q_m) obtained from the slopes are 151.5 mg/g for Cu^{2+} and 115.0 mg/g for Cd^{2+}, with Langmuir constants (K_L) of 0.086 L/mg and 0.071 L/mg, respectively.

3.4 Kinetic Evaluation

Table 7 presents the kinetic parameters for Cu^{2+} and Cd^{2+} adsorption onto sulfuric acid-activated watermelon peel. The pseudo-second-order (PSO) model best fits both metals, with correlation coefficients (R^2) greater than 0.985. This suggests that the adsorption process is likely controlled using chemisorption mechanisms, such as valence-force sharing or ion exchange, rather than by boundary layer diffusion

Table 7: Kinetic model parameters for Cu^{2+} and Cd^{2+} adsorption.

Metal	K_1 (PFO)	R^2	K_2 (PsO) (g mg^{-1} min^{-1})	R^2
Cu^{2+}	0.054	0.741	0.0091	0.987
Cd^{2+}	0.047	**0**.698	0.0075	0.985

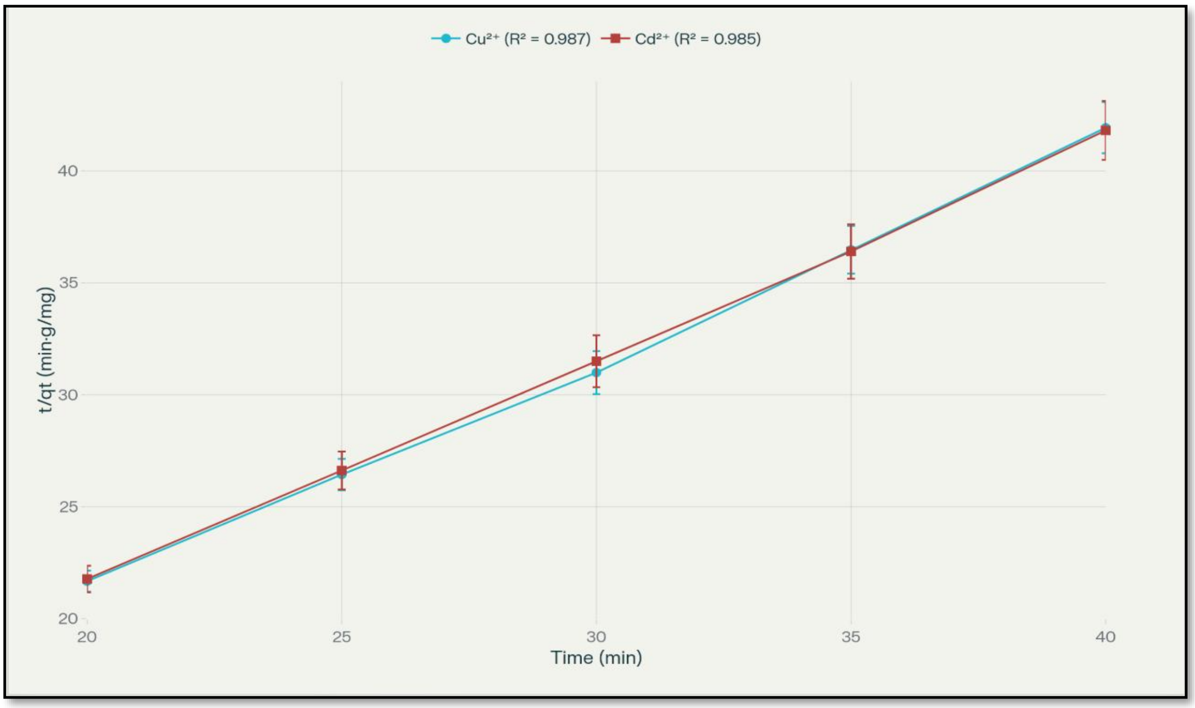

Figure 4. Pseudo-second-order linear plots of t/q_t versus t

Pseudo-second-order (PSO) kinetic model linear plots for Cu^{2+} and Cd^{2+} adsorption, illustrating the relationship between t/q_t and time, are shown in Figure 4. The excellent linear fit ($R^2 > 0.985$) confirms that the process of adsorption follows PSO kinetics, suggesting chemisorption as the rate-limiting mechanism. The pseudo-second-order rate constants (k_2) are 0.0091 g mg⁻¹ min⁻¹ for Cu^{2+} and 0.0075 g mg⁻¹ min⁻¹ for Cd^{2+}. Error bars indicate the standard deviation (n = 3) from propagated experimental uncertainties.

3.5 Comparative Performance

Table 8 presents a comparison of the maximum adsorption capacities (Q_m) for Cu and Cd ions achieved with different biosorbents. The sulfuric acid-activated watermelon peel prepared in this study shows a Cu adsorption capacity of 151.5 $mg^{-1}g^{-1}$ and a Cd adsorption capacity of 115.0 $mg^{-1}g^{-1}$, demonstrating comparable performance to watermelon peel biochar activated with 50% H_2SO_4 reported by El-Nemra *et al.* [5]. Our adsorbent surpasses the magnetic-modified watermelon peel composite and closely matches the performance of chemically activated biochar, validating the effectiveness of sulfuric acid activation.

Table 8: Comparative maximum adsorption capacities of biosorbents for the removal of Cu^{2+} and Cd^{2+} ions

Biosorbent (Year)	Activation	Q_m-Cu (mg/g)	Q_m-Cd (mg/g)	References
Watermelon peel biochar-S (2022)	50% H_2SO_4	151.5	-	[5]
Raw WMP rind (2022)	None	357.1	115.0	[15,22]
Melon peel + $CoFe_2O_4$ (2021)	Magnetic	106.4	65.4	[17]
Banana peel AC (2020)	$ZnCl_2$	128,0	97.3	[4]
This study	1M H_2SO_4	151.5	115.0	-

3.6 Regeneration and Reuse

Desorption with 0.1 M HNO_3 restores 94.1% Cu^{2+} capacity after the first cycle, declining to 85.3% by the third. Comparable stability noted for amine-modified WMP (three cycles, 83% retention). Acidic eluent costs ≈$0.09/kg adsorbent; economic assessment favours 5-cycle reuse.

4. Conclusion

Sulfuric acid-activated watermelon peel exhibited robust monolayer adsorption performance, achieving capacities of 151.5 mg/g for Cu^{2+} and 115.0 mg/g for Cd^{2+}, reflecting its strong affinity and high uptake potential for these heavy metal ions. The adsorption process follows pseudo-second-order (PSO) kinetic behaviour, suggesting that chemisorption involving electron sharing or exchange is the predominant mechanism governing metal ion binding. Additionally, the adsorbent demonstrates excellent regeneration efficiency over multiple reuse cycles, while the low cost and widespread availability of watermelon peel as an agricultural by-product underscore its potential as a sustainable and economically viable adsorbent. These attributes position sulfuric acid-activated watermelon peel as a promising candidate for decentralized wastewater treatment applications, especially in resource-limited settings where affordable heavy metal remediation technologies are urgently required.

Author's Declarations

All of the authors worked together to complete this work. The final manuscript was read and approved by each author.

Conflict of Interest

The authors declare no conflicts of interest related to this work.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Authors' Contributions

Archibong, U. D. and Don, J. U. contributed to the literature search, data organization, and manuscript drafting. Both authors revised the manuscript for intellectual content, developed the conceptual framework, validated data, supervised the study, and coordinated the writing process. All authors approved the final version.

Ethical Declarations – Human/Animal Studies

Not applicable.

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