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Synthesis of Chitosan from Calappa Pustulosa Shell for the Removal of Heavy Metals in Borehole Water in Some Selected Basic Schools in Effia-Kwesimintsim Metropolis in the Western Region of Ghana

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Abstract
The heavy metal contamination of borehole water in basic schools is a serious environmental problem in the Effia Kwesimintin Metropolis, Sekondi-Takoradi in the Western Region of Ghana. This research looked at how well synthetic chitosan worked as an adsorbent to remove heavy metals from borehole water in a sample of elementary schools. With maximum adsorption capacities of 93.5, 87.5, and 67.5% for lead, cadmium and arsenic respectively, the findings showed that chitosan had a high adsorption capacity for these metals. The adsorption data were well-fitted to the linear Langmuir isotherm model indicating monolayer adsorption, with maximum monolayer coverage (Q_{max}) of the synthesized chitosan, the Langmuir constant (K_L), the Langmuir separation factor (R_L) and R^2 values were found to be 59.3356mg/g, 0.01931/mg, ($35.3E^{-03}$ – $771.0E^{-03}$) and (0.9945-0.9973) respectively. The study demonstrates the potential of synthesized chitosan as a low-cost and sustainable adsorbent for the remediation of heavy metals from borehole water in some selected basic schools.

Keywords: Calappa pustulosa shells, Chitosan, Mutagenic, Batch adsorption, Monolayer adsorption, Adsorption capacities, and Langmuir isotherm model.

INTRODUCTION

Access to safe, potable water is crucial for children's health, especially in schools in the Western Region of Ghana. Borehole water in schools is often contaminated with toxic metals like arsenic, cadmium, and lead, which can cause cancer and damage to the kidneys and nervous system. Adsorption methods, such as using non-toxic biodegradable polysaccharides like chitosan, have shown efficacy in removing these metals. Chitosan, a non-toxic and biodegradable polysaccharide, can be easily modified to improve its adsorption capacity and selectivity. It is a structural component of marine shells and found in mollusks, insects, crustaceans, fungus, and algae. The study investigates the effectiveness of synthesized chitosan as an adsorbent for removing heavy metals from borehole water in Ghana's Effia-Kwesimintim Metropolis. The water, often polluted with heavy metals like lead, cadmium, and arsenic, poses significant health risks to children and pregnant mothers. The amine group facilitates strong electrostatic interactions with other inorganic chemicals, making adsorption a common method for removing heavy metals from water. The research emphasizes the urgent need for practical and ecologically sustainable methods to reduce heavy metals from borehole water in schools.

Quality Control

All the glassware were thoroughly washed in a solution of laboratory detergents (TEEPOL), well rinsed in double deionized water, and dried at 130 °C to avoid contamination. Laboratory quality control measures were also followed during the analysis of each set of samples collected.

Methodology

Sample Collection

Borehole water samples were collected from 10 schools in the Effia kwesimintim Metropolis, Sekondi-Takoradi, Western Region, Ghana. The samples were collected into 5 L high-density polyethylene (HDPE) bottles, which were immersed in aqua regia for 24 hours, cleansed, and rinsed three times. The bottles were then dried on a ceramic bench. Thirty borehole samples were collected, with each triplicate collected in triplicate. The water was pumped out of the system to ensure depth. The samples were then acidified with concentrated nitric acid, labeled, sealed, and transported to the laboratory in an ice chest.

Synthesis of Chitosan

Chitosan is a chemical compound made from crab shell debris, specifically Calappa pustulosa, which is purchased from vendors in the Western Region of Ghana. The shells are cleaned and crushed to powder, then stored in airtight containers for production. The process involves demineralizing and deproteinizing the shells, then treating them with sodium hydroxide. The shells are dried in an oven at 40°C for 30 minutes before cooling to room temperature. To remove minerals, 40g of the powdered sample is treated with 2 M HCl solution for 24 hours at 80°C. The sample is then deproteinized with 2 M NaOH solution at 110°C for 20 hours at a 1:10 solid-to-solution ratio. Acetone is added for decolorization and production of a chitin mixture. The chitin mixture is then filtered, rinsed with distilled water, dried in an oven at 40°C, and allowed to cool to room temperature. The residue is treated with a 50% concentrated NaOH solution at 150°C for 4 hours to remove the acetyl groups of chitins. The residue is then rinsed multiple times with distilled water to achieve neutral pH, dried, and stored for heavy metal extraction.

Reagents / Chemicals

Analar 36 % hydrochloric acid, Analar concentrated nitric acid, Sodium hydroxide, Lead nitrate and Acetone

Materials

Calappa pustulosa shells

Preparation Standard Solution

A 90 mg/L lead solution was prepared by dissolving 5.3 mg analytical grade $Pb(NO3)_2$ powder in distilled water and the resulting solution stored as a stock solution. A 56 mg/L solution was prepared by diluting the stock solution.

Preparation of 3:1 v/v Aqua Regia (11.50 M HCl: 15.5 M HNO_3)

The aqua regia procedure put forth by Nieuwenhuize et al. (1991) for trace element digestion was followed (Sastre, Sahuquillo, Vidal, & Rauret, 2002). Exactly, 150 mL of 36 % Analar hydrochloric acid (11.50 M HCl) was added to 50 mL (69.0 to 70.5) % Analar nitric acid (15.5 M HNO_3).

Preparation of 3 % Hydrochloric Acid Solution

Thirty milliliters of 36 % Hydrochloric acid was diluted with 970 mL of deionized water to 1 L.

Physico-chemical Parameters of Borehole, Water Samples

The results obtained for the analysis of the physico-chemical parameters of the borehole water samples such as the temperature, pH and the conductivity of all samples are presented (Table 1).

Table 1: Mean Physico-Chemical Parameters Borehole Water Before and After Treatments

Sampling Code	Age /yr	RI/(m)	pH before	pH after	Temp. before/^{O}C	Temp. after/^{O}C	conductivity /(µs/cm)
BH1	12	2.46	7.01	6.90	28.60	28.88	0 .081
BH2	5	1.60	6.68	6.91	29.90	28.85	0.040
BH3	6	3.71	6.84	6.82	30.00	28.82	0.043
BH4	3	4.79	6.94	6.92	30.20	28.89	0.039
BH5	7	4.80	7.28	6.99	30.20	28.84	0.040
BH6	9	4.80	6.86	6.80	30.30	28.91	0.038
BH7	7	4.80	7.07	7.20	30.20	28.77	0.038
BH8	30	2.40	6.99	7.10	30.10	28.89	0.040
BH9	12	3.20	6.83	6.80	30.20	28.66	0.041
BH10	8	2.40	6.92	6.98	30.10	28.83	0.038
Total 10							

Source: Field and laboratory work (2025)

Keys: Radius of Influence (RI), Borehole (BH)

The pH of borehole water samples ranged from 6.68 to 7.28, with an average of 6.98. The pH limits set by the World Health Organization (WHO) fall within the 6.5 to 8.5 range for drinking and domestic purposes. Temperature also affected the solubility of gases and the rate of chemical reactions in water. The electrical conductivity (EC) values of borehole water samples from various schools ranged from 28.72 to 30.25 oC. The conductivity values of the water were 0.068 µs/cm, 0.039 µs/cm, 0.038 µs/cm, 0.041 µs/cm, 0.040 µs/cm, 0.042 µs/cm, 0.040 µs/cm, 0.038 µs/cm, and 0.041 µs/cm, respectively. The low conductivities recorded in all borehole waters ranged from 0.038 to 0.068 µs/cm, indicating very few ions present in the samples, compared to the WHO acceptable limit of 700 µs/cm at 25 oC. This suggests that the borehole water samples in basic schools are suitable for drinking and domestic consumption.

Digestion of Borehole Water Samples for Arsenic, Lead and Cadmium

A 250 mL conical flask was used to digest borehole water with 50 mL of aqua regia (3:1 HCl: HNO3). The mixture was stirred and digested at 106 degrees Celsius to prevent arsenic, lead, and cadmium losses. Full digestion occurred when the treated solution was reduced to around 2 mL and brown nitrogen dioxide gas stopped. The digested solutions were cooled, then transferred to a 100 mL plastic sample container containing doubly deionized water and diluted. The residual arsenic, lead, and cadmium in the digest were measured using an atomic absorption spectrometer.

Treatment of Digested Borehole Water Samples with Chitosan

Hundred milliliters for each bore-hole water samples were measured and analyzed using atomic adsorption spectroscopy to determine the initial levels of lead, cadmium and arsenic present in the water. Adsorption efficiency studies were conducted by adding 50 mg mass of the synthesized chitosan to each 100 mL samples and 50 ml of 56 mg/L $Pb(NO3)_2$ solution added, stirred on a hotplate magnetic stirrer for 2 hours at (30°C) to obtain an sparingly insoluble mixture. The mixture was then filtered and 100 ml of the filtrate measured for the determination of the levels of lead absorbed by chitosan using AAS.

Data Analysis

The adsorption data were analyzed using, the mean level and standard deviations, the paired sample T-Test, and the Langmuir isotherm model to determine the maximum adsorption capacity of chitosan.

Discussion

The results of this study showed that synthesized chitosan is a promising adsorbent for the remediation of heavy metals from borehole water in basic schools. The adsorption capacity of chitosan for lead, cadmium and arsenic was high, indicating that chitosan has a strong affinity for these metals. The adsorptions were well-fitted to the Langmuir isotherm model, indicating monolayer adsorption. The results of this study suggest that synthesized chitosan can be used as a low-cost and sustainable adsorbent for the remediation of heavy metals from borehole water in basic schools.

Table 2: Mean Levels and Standard Deviations of Lead, Cadmium, and Arsenic in Untreated Borehole Water Samples (mg/ L)

Sample code	Pb (mean ± SD) xE^{-02}	Cd (mean ± SD) xE^{-02}	As (mean ± SD) xE^{-02}
BH1	1081.4 ± 37.0	38.4 ± 5.9	228.7 ± 70.8
BH2	1273.8 ± 88.9	64.9 ± 5.8	230.1 ± 15.6
BH3	1354. 9 ± 89.1	44.7 ± 5.2	199.9 ± 59.4
BH4	1572.5 ± 64.3	45.6 ± 5.4	270.7 ± 33.1
BH5	1644.1 ± 90.0	39.0 ± 2.2	287.4 ± 29.3
BH6	112.4 ± 121.7	29.7 ± 8.5	287.9 ± 40.3
BH7	353.0 ± 512.0	33.9 ± 21.2	260.8 ± 83.1

BH8	150.3 ± 98.0	19.2 ± 0.3	258.6 ± 6.5
BH9	905.0 ± 1250.0	33.1 ± 2.0	244.7 ± 47.5
BH10	36.8 ± 106.1	35.2 ± 5.9	229.4± 27.6

Table 2 shows that the mean concentrations and standard deviations (SD) of lead (Pb), cadmium (Cd), and arsenic (As) in untreated borehole water vary across various localities. Borehole 5 had the highest lead (Pb) contents (1644.1 ± 90.0 mg/L), suggesting serious pollution. Borehole 10 had the lowest levels (36.8 ± 106.1 mg/L). Cadmium (Cd) values were greatest in borehole 2 (64.9 ± 5.8 mg/L) and lowest in borehole 8, 19.2 ± 0.3 mg/L. Arsenic (As) concentrations were very stable, ranging from 199.9 ± 59.4 mg/L (borehole 3) to 287.9 ± 40.3 mg/L (borehole 6).

The study revealed that chitosan treatment significantly altered lead and cadmium concentrations in some boreholes, but not in others. There were also variations in arsenic content, suggesting less consistent removal. However, individual samples showed varying results due to parameters, treatment effectiveness, or environmental impacts. The statistical significance suggests that chitosan effectively reduced heavy metal pollution in groundwater.

Table 3: Paired Sample T-Test on Borehole Water Samples for the Lead, Cadmium and Arsenic after Treatment with Chitosan

	P		Cd		As	
	Test Statistic	P-value	Test Statistic	P-value	Test Statistic	P-value
BH1	41.34	0.015	9.28	0.068	4.57	0.137
BH2	20.25	0.031	11.13	0.057	20.92	0.030
BH3	21.51	0.030	12.09	0.053	4.76	0.132
BH4	34.55	0.018	11.85	0.054	8.17	0.078
BH5	25.84	0.025	25.14	0.025	13.86	0.046
BH6	1.31	0.416	4.97	0.126	10.11	0.063
BH7	0.98	0.508	2.26	0.265	4.44	0.141
BH8	2.17	0.275	103.54	0.006	55.91	0.011
BH9	1.02	0.492	23.20	0.027	7.29	0.087
BH10	0.49	0.710	8.47	0.075	11.75	0.054

Significance level = 5

Table 4: General Paired Sample T-Test on Borehole Water Samples

Metal	Test Statistic	P-Value
Pb	7.71	0.000
Cd	18.13	0.000
As	35.64	0.000

The Percentage Removal Efficiency

Percentage removal efficiency (%) = $[(C_o-C_e)/C_o]$ x 100--------------------(1)

where C_o and C_e represent the initial and equilibrium concentrations of heavy metal ions in mg/L, respectively.

Table 5: Percentage Removal Efficiencies for the Lead, Cadmium and Arsenic

	Pb(%)	Cd(%)	As(%)
BH 1	86.4	75.7	48.1
BH 2	91.2	87.5	50.6
BH 3	87.0	84.4	43.5
BH 4	93.5	77.3	61.2
BH 5	90.8	76.4	67.8
BH 6	44.2	75.8	61.4
BH 7	72.4	67.9	55.1
BH 8	49.5	53.2	63.6
BH 9	89.3	66.6	56.2
BH 10	18.9	70.4	61.1

From Table 5, it can be seen that the highest percentage removal of lead was about ninety-four percent (93.5%) whiles the least was about nineteen percent (18.9%) for borehole 4 and 10 respectively. Likewise, borehole 2 showed the highest cadmium removal (87.5%) whiles borehole 8 showed the least cadmium removal (53.2%). Equally, the highest arsenic (As) removal was in borehole 5 (67.8%) and the lowest was borehole 3 (43.5%). This Table cements the outcome of in Table 2 and 3 which showed that synthesize chitosan generally removes lead and cadmium better than arsenic. The variations suggest that while chitosan generally performed well, factors like adsorption kinetics, water chemistry, and metal-binding interactions influenced efficiency.

Batch Adsorption Experiments using Synthesized Chitosan

Batch adsorption experiments were conducted to evaluate the adsorption capacity of chitosan for lead, cadmium, and arsenic. The study was performed at room temperature to be representative of environmentally relevant conditions. The volume(V) borehole water was kept constant. The adsorption capacity of chitosan was calculated using the following equation:

$q = (C_0 - Ce) \times V / m$--------------------(2)

Where q is the adsorption capacity, C_0 is the initial metal concentration, Ce is the equilibrium metal level, V is the volume of the solution, and m is the mass of chitosan.

Adsorption capacity measures how much metal was removed per unit of adsorbent. From Table 6, lead (Pb) adsorption was highest in borehole 5 (32.88 mg/g), followed by borehole 4 (31.45 mg/g), showing strong chitosan binding. Borehole 10 had the lowest (0.734 mg/g), suggesting poor Pb adsorption. Meanwhile, cadmium (Cd) adsorption was highest in borehole 2 (1.4218 mg/g), showing efficient removal, while borehole 8 had the lowest (0.3832 mg/g). In the same way, arsenic (As) adsorption showed relatively consistent values, with borehole 5 (5.746 mg/g) and borehole 6 (5.758 mg/g) performing best.

Table: 6 Adsorption Capacity (q) for the Lead, Cadmium and Arsenic in mg/g

Sampleing code	Pb	Cd	As
BH 1	21.628	0.767	4.576
BH 2	25.476	1.422	4.602
BH 3	27.098	0.894	3.998

BH 4	31.450	0.912	5.414
BH 5	32.880	0.779	5.746
BH 6	2.250	0.593	5.758
BH 7	7.080	0.678	5.216
BH 8	3.006	0.383	5.172
BH 9	18.100	0.661	4.896
BH 10	0.734	0.703	4.590

These findings indicate that while synthesize chitosan effectively adsorbed heavy metals, its performance varied depending on metal type and borehole conditions. Further optimization may be required to improve adsorption in boreholes with lower efficiency.

Equilibrium study

Adsorption isotherms are mathematical models that relate the amount of the adsorbate adsorbed onto the adsorbent and the residual amount of the adsorbate in the aqueous phase when the adsorption process has attained equilibrium. The adsorption data were analyzed using the linear form of Langmuir isotherm model equation to determine the maximum adsorption capacity of chitosan. The Langmuir isotherm is represented by the linear form:

$q_e = (1/q_{max}K_L) + (Ce/q_{max})$--------------------(3)

where qe (mg/g) and Ce (mg/L) are equilibrium solid and liquid phase concentrations of adsorbate, respectively and q_{max} (mg/g), the maximum amount of metal ions adsorbed per unit mass or volume of adsorbent. An essential dimensionless parameter (R_L), a characteristic of the Langmuir isotherm is expressed as:

$R_L = 1/(1+K_LC_e)$--------------------(4).

The dimensionless parameter (R_L) is the separation factor and it determines whether the adsorption process is favourable or unfavourable.

Where, q_e is heavy metal concentration on the Chitosan at equilibrium (mg /g); q_{max} (mg/g) and K_L(1/mg) are Langmuir constant related to be maximum adsorption capacity corresponding to complete coverage of available adsorption sites and a measure of adsorption energy (equilibrium adsorption constant), respectively. These constants are determined from the slope and the intercept from a linear plot of (Ce/q_e) against Ce, so that

$q_{max} = 1$ / slope and K_L = slope/intercept--------------------**(5)**

Table 7: Linear Langmuir Isotherm Constants for Adsorption of Pb, Cd, and As on Chitosan at room temperature (30 °C).

Heavy metal	q_{max}	K_L	R^2	R_L
Pb	59.3356	0.0193	0.9973	0.0353
Cd	59.3356	0.0193	0.9945	0.4073
As	59.3356	0.0193	0.9945	0.7717

The Langmuir isotherm was used to analyze adsorption data on chitosan, with values of qmax and KL being 59.3356 mg/g and 0.0193 L/mg for all three metals. The separation factor RL values ranged from 0.0353 to 0.7717, indicating the adsorption of lead, cadmium, and arsenic onto the chitosan. The applicability of isotherm models was evaluated by judging the correlation coefficient, R2 values. The isotherm with R2 close to unity (R2=1) was selected as the best fit, explaining the adsorption process. The adsorption isotherm data was then fitted to these models to find the most suitable model for the study.

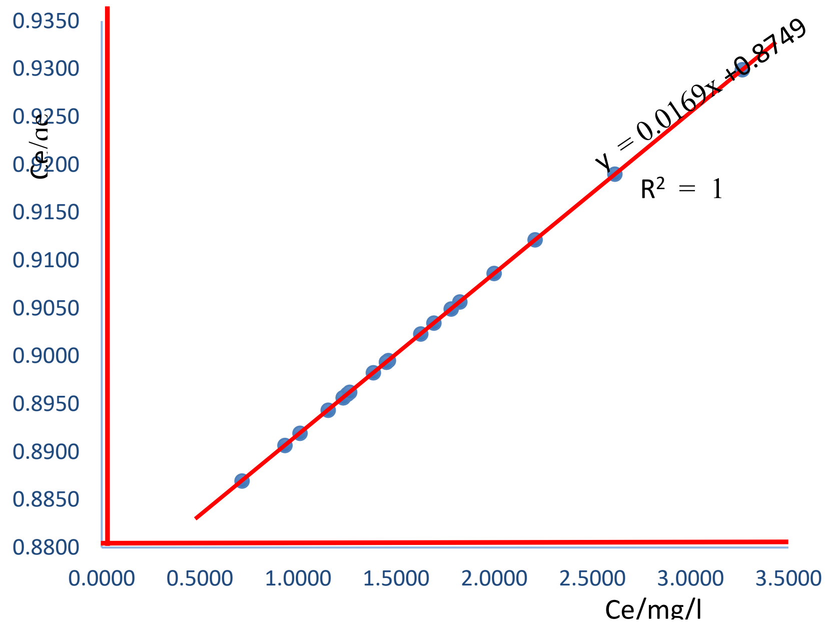

Figure 1a: Langmuir Adsorption Isotherm for lead (II) ions

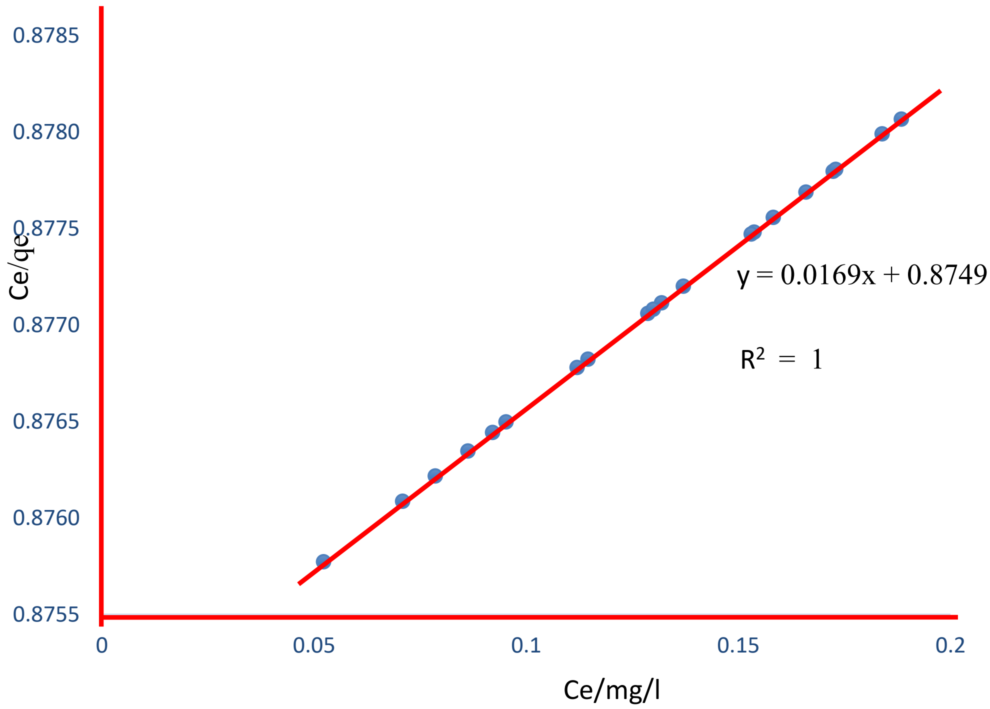

Figure1b: Langmuir Adsorption Isotherm for arsenic and cadmium ions

The study found that the linear Langmuir isotherm model provides a good model for adsorption in lead, cadmium, and arsenic systems. The lead isotherms fit better than cadmium and arsenic. Synthesized chitosan is a viable adsorbent for heavy metal remediation from well water, with high adsorption capacity for these metals. The adsorption data fit the Langmuir isotherm model, indicating monolayer adsorption. This suggests chitosan can be used as a low-cost and sustainable adsorbent for water remediation. The use of Calappa pustulosa shell as a source of chitin is also a sustainable and environmentally friendly approach. Further studies can be conducted to optimize the synthesis process and evaluate the effectiveness of the synthesized chitosan in removing other heavy metals.

Conclusion

In conclusion, this study has demonstrated the effectiveness of synthesized chitosan as an adsorbent for the remediation of heavy metals from borehole water in basic schools. The results of this study suggest that synthesized chitosan can be used as a low-cost and sustainable adsorbent for the remediation of heavy metals from borehole water in basic schools. Therefore, it is recommended that synthesized chitosan be used as an adsorbent for the remediation of heavy metals from borehole water in basic schools in the Effia-Kwesimintim Metropolis, Sekondi-Takoradi, Western Region, Ghana.

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