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Isotherm and Kinetic Studies on *Escherichia coli* for Cadmium-Contaminated Wastewater Treatment

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ABSTRACT

Background and Objective: Cadmium (Cd) contamination poses a major environmental and public health concern due to its toxicity, persistence, and bioaccumulation. Conventional remediation methods are often costly and inefficient, generating secondary pollution. This study aimed to evaluate the biosorption potential of *Escherichia coli* isolated from a plastic recycling plant for the removal of Cd (II) ions from aqueous solutions, using isotherm and kinetic modeling to characterize adsorption behavior. **Materials and Methods:** Soil samples from a plastic recycling site were processed to isolate *E. coli*, identified through Gram staining and biochemical tests. Biomass was prepared and used in batch biosorption experiments under varying pH, contact time, initial Cd concentration, and biomass doses. Residual Cd levels were measured using atomic absorption spectrophotometry (AAS). Adsorption data were analyzed using Langmuir and Freundlich isotherms and kinetic models, including pseudo-first and pseudo-second order equations. **Results:** Maximum Cd (II) uptake occurred at pH 7, with equilibrium reached within 24-28 hrs. Adsorption capacity increased with initial Cd concentration until saturation. The pseudo-first order kinetic model best fitted the data, while the Langmuir isotherm showed the highest correlation, indicating monolayer adsorption on homogeneous sites. The maximum adsorption capacity was 50.013 mg/g. **Conclusion:** The findings confirm that *E. coli* biomass serves as an effective, low-cost biosorbent for Cd (II) removal under laboratory conditions. Its performance aligns with established biosorption models, supporting its potential application in wastewater treatment. Further studies on regeneration efficiency, column operations, and molecular adsorption mechanisms are recommended for practical implementation.

KEYWORDS

Escherichia coli biomass, cadmium (Cd) removal, biosorption, Langmuir isotherm, adsorption kinetics, low-cost biosorbent, plastic recycling waste, wastewater remediation, circular economy

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INTRODUCTION

Industrialization and expanding plastic-related activities have increased heavy-metal inputs to the environment; Cd is particularly problematic due to toxicity, persistence, and bioaccumulation[1]. Recent reviews document the environmental impacts of plastic recycling and related waste streams on metal contamination[2]. Anthropogenic activities and improper waste handling further exacerbate environmental degradation and the need for affordable remediation technologies[3].

Conventional physicochemical treatments (e.g., chemical precipitation, ion exchange) are effective but often costly and can generate secondary wastes; adsorption and biosorption are attractive low-cost alternatives[4]. Biosorption passive binding of metal ions onto the surfaces of biological materials, has been widely studied for Cd, Pb, Cu, and other heavy metals[5]. Proper application of isotherm and kinetic models (Langmuir, Freundlich, pseudo-first and pseudo-second order) is essential to interpret sorption behaviour and to guide scale-up[6].

Biomasses used for biosorption include microbial cells and agricultural/industrial wastes (nutshells, husks, pods), and many studies have demonstrated high sorption capacities for such materials[7]. Comprehensive reviews of low-cost adsorbents show consistent patterns in capacity, kinetics, and influencing factors that can guide *Experimental design*[8]. Local agricultural residues and microbial isolates are especially attractive in resource-limited settings because they are inexpensive and locally available[9-12].

Several studies have characterized adsorption kinetics and isotherms for groundnut husk, Senna tora (modified and unmodified), and Dennettia tripetala, providing benchmarks for both isotherm parameters and kinetic regimes[13-15]. Works on alginate composites, LDH intercalates, and polymeric hydrogels illustrate engineered biosorbents with high capacities and are helpful comparators for microbial systems[16]. Guidance on correct isotherm selection, linearization pitfalls, and interpretation is essential to prevent misapplication of models[17-21].

This study isolates *E. coli* from a plastic recycling plant and evaluates Cd (II) biosorption across pH, contact time and concentration ranges.

MATERIALS AND METHODS

Study area and sample collection: The research was conducted at the Microbiology Laboratory of the Federal University, Wukari, Taraba State, Nigeria, over six months (January to June, 2024). Wukari, a historically significant city formerly part of the defunct Gongola State, is strategically located between Taraba and Benue States. Geographically, it is bounded to the south by Benue State, to the north by Gassol Local Government Area (LGA), to the East by Donga LGA and Takum, and to the West by Ibi LGA.

Climatic conditions in Wukari are characterized by relative humidity ranging from 14 to 77%. The city covers a land area of 4,308 km^2 and recorded a population of approximately 241,546 during the 2006 national census. Beyond its demographic and geographic attributes, Wukari is recognized as a traditional state with a rich cultural heritage, encompassing diverse norms, values, and practices that contribute to its socio-cultural identity[22].

Sample collection: A sampling site was precisely mapped out for soil sample collection, which was a plastic recycling site at Ambassador Roundabout, Wukari, Taraba State. Samples were stored at 4°C and processed within 24 hrs.

Materials: Hand gloves, cotton wool, Nutrient Agar (NA), MacConkey Agar (MA), Potato dextrose Agar (PDA), petri dish, masking tape, distilled water, wire loop, dropper, syringe and needle, measuring cylinder, test-tube, autoclave, weighing balance and pH meter, Spectrophotometer, Shakers, and Beakers.

Media preparation: The various media (PDA), Potato Destrose Agar, (MCA) MacConkey Agar, (NA) Nutrient Agar, were weighed according to the manufacturer's instructions and sterilized at 121°C for 15 min at 15 PSI.

After sterilization, it was allowed to cool to a temperature bearable to the skin.

Isolation and identification of *E. coli*: Serial dilutions were plated on MacConkey and Nutrient agar, and distinct colonies were purified. Phenotypic identification used Gram staining and standard biochemical tests (indole, citrate, TSI, catalase, oxidase)[23]. Selected isolates were maintained for biosorption assays[24].

Preparation of biosorbent and reagents: Biomass was produced by culturing the chosen *E. coli* isolate in nutrient broth overnight, harvesting by centrifugation, washing three times with deionized water and using either wet biomass or oven-dried biomass as indicated. Analytical-grade CdCl was used to prepare stock and working solutions[25-27].

Batch biosorption experiments: Batch experiments were carried out with 100 mL working volume in 250 mL flasks. Parameters tested: Initial Cd concentration (5-50 mg/L), pH (3, 5, 7, 9), contact time (0-48 hrs), and biomass dose (0.1-1.0 g/100 mL). After contact, samples were centrifuged and supernatants analysed for residual Cd by AAS. Percent removal and qe (mg/g) were calculated using standard mass-balance equations[28]. *Experimental design* and batch vs fixed-bed considerations followed established guidance[29].

Isotherm and kinetic modelling: Equilibrium data were fitted to Langmuir and Freundlich isotherms; kinetics were analysed with pseudo-first and pseudo-second order models. Linear and non-linear regression approaches were used; fits were assessed by R^2 and error metrics following recommended practice[17]. Representative comparators and modelling strategies from the literature were used to ensure robust parameter estimation[30].

Data analysis: All experiments were performed in triplicate and results were reported as Mean±SD. Curve fitting and statistics were performed using standard software[31].

RESULTS

Identification and biochemical profile of the isolate: The selected isolate demonstrated morphological and biochemical traits consistent with *Escherichia coli* (Gram-negative rods; indole positive in the tested strain)[23].

Table 1 summarizes the biochemical test results used to identify the Escherichia coli isolate. The table lists Gram staining, enzymatic activities, sugar fermentation profiles, and growth characteristics on MacConkey agar. These results confirm the morphological and biochemical traits consistent with *E. coli*.

Biochemical characteristics of bacterial isolates from the plastic recycling plant site. Data include Gram reaction, enzyme tests, sugar fermentation patterns, and colony morphology on MacConkey agar.

Effect of contact time: Adsorption occurred rapidly during the initial phase (0-8 hrs) and approached steady state by ~24-28 hrs. This time course is consistent with sorption profiles reported for microbial and plant-based biosorbents[32].

Figure 1 presents the contact time profile for Cd (II) biosorption by *Escherichia coli*. The curve shows a rapid uptake within the first 8 hrs, followed by a slower approach to equilibrium at 24-28 hrs.

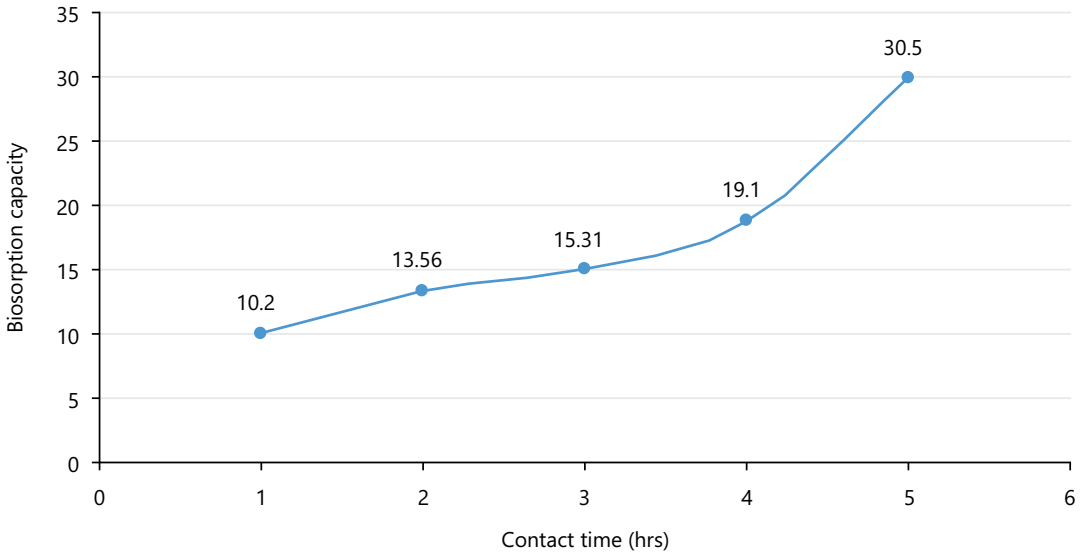

Fig. 1: Effect of contact time on the biosorption of Cd (II) ions by *Escherichia coli* isolated from a plastic recycling plant (Self-generated)

Effect of contact time on Cd (II) biosorption by *Escherichia coli* biomass. The plotted curve shows adsorption capacity (q) over time, with data points representing mean values from triplicate experiments

Table 1: Biochemical test for *E. coli*

Code	Gram Staining	Catalyst Test	Coagulase Test	Simon citrate test	Glucose test	Sucrose test	Galactose test	Oxidase
MacConkey Agar Plate1 White	Rod-Chain Shape (Purple)	+	-	+	-	-	-	+
MacConkey Agar Plate1 Pale Yellow	Cocci (Purple)	+	-	-	+	-	-	+
MacConkey Agar Plate 2 Yellow	Rod Shape (Purple)	+	-	-	+	-	-	-
MacConkey Agar Plate 2 White	Rod Shape (Purple)	+	-	-	+	+	+	+
MacConkey Agar Plate1 Yellow	Cluster Rod Shape (Purple)	+	-	-	+	+	+	-
MacConkey Agar Plate1 White	Rod Shape (Purple)	+	+	-	-	-	-	-
MacConkey Agar Plate 2 Yellow	Rod shape (Purple)	+	-	-	-	-	-	+
Plate 2 Yellow	Rod shape (Purple)	+	-	-	-	-	-	-
Plate1 White	Rod shape (Purple)	+	+	+	+	+	+	-
Plate1 Yellow	Rod shape (Purple)	+	-	+	+	-	-	-
Plate 3 Yellow	Cocci (Purple)	-	-	-	+	+	+	-

Effect of solution pH: Maximum uptake occurred at neutral pH (pH 7); adsorption decreased at low pH (proton competition) and at very high pH (possible precipitation/speciation effects). These pH dependencies align with widely reported observations for biosorbents[33].

Figure 2 illustrates the pseudo-first-order kinetic model fit for Cd (II) biosorption. The linear plot of log(qe-qt) versus time demonstrates a strong correlation between experimental and model-predicted values. This supports the conclusion that pseudo-first-order kinetics best describe the system.

Effect of initial metal concentration and biomass dose: The qe increased with initial concentration until a plateau, indicating sorbent saturation was reached; increasing biomass dose increased total removal but lowered qe (mg/g) due to site distribution effects, as discussed in batch vs column comparisons[34].

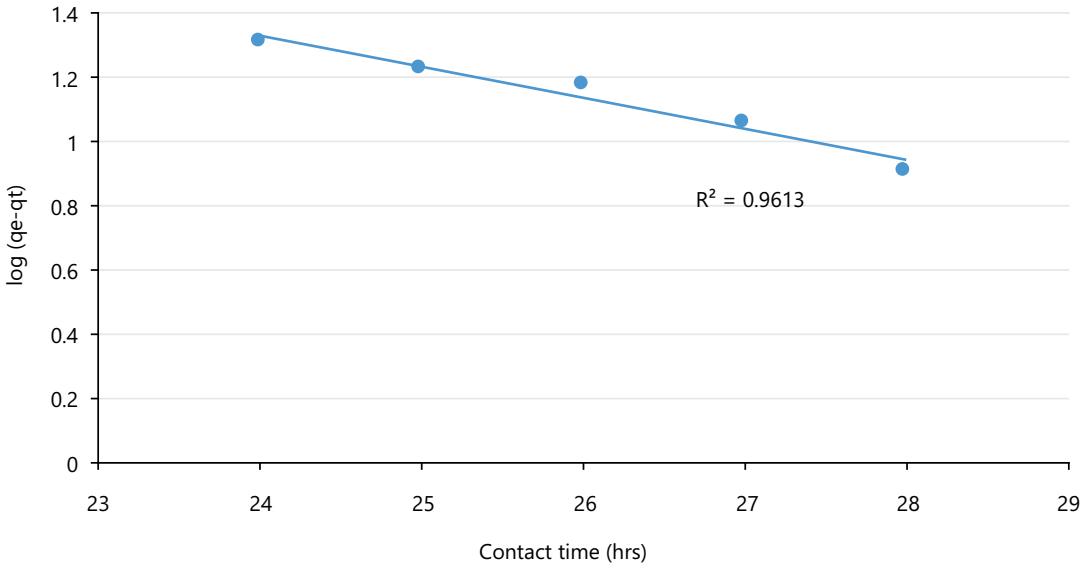

Fig. 2: The pseudo-first order model plot for the biosorption of Cd ions by *Escherichia coli* isolated from a plastic recycling plant. It's a plot of log (qe-qt) versus t derived from the pseudo-first order linear equation (Self-generated)

Pseudo-first order kinetic model plot for Cd (II) biosorption by *Escherichia coli*. The straight-line fit shows log(qe-qt) against contact time, with slope and intercept used to determine kinetic parameters

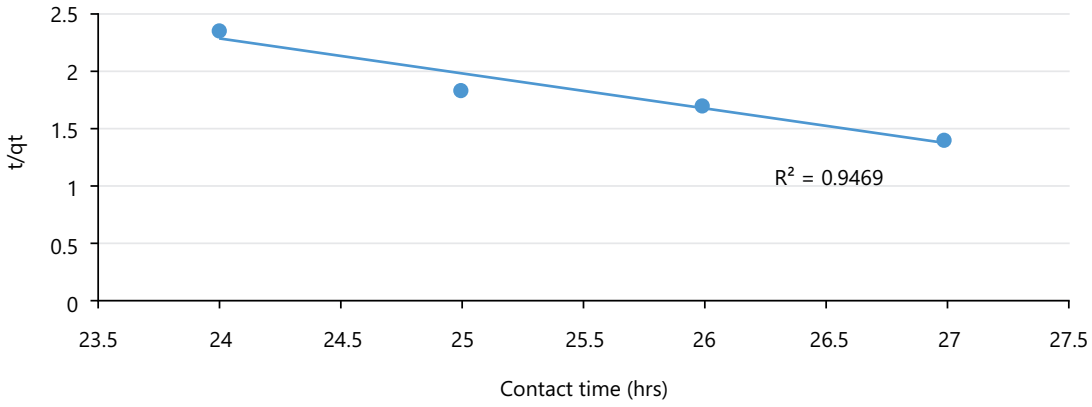

Fig. 3: The pseudo-second order model plot for the biosorption of Cd ions by *Escherichia coli* isolated from a plastic recycling plant. It's a plot of log t/qt versus t derived from the pseudo-first order linear equation (Self-generated)

Pseudo-second order kinetic model plot for Cd (II) biosorption by *Escherichia coli*. The graph displays t/qt against contact time, with the slope and intercept used to calculate kinetic constants

Figure 3 shows the pseudo-second order kinetic model plot for Cd (II) biosorption. The t/qt versus time relationship indicates a reasonable fit, though slightly less accurate than the pseudo-first order model. This comparison aids in identifying the dominant adsorption mechanism.

Kinetic modelling: Kinetic curves fitted both pseudo-first and pseudo-second order models reasonably; pseudo-first order produced a slightly better R^2 and qcalc agreement with qexp for these data (Table 2)[35].

Table 2 presents the kinetic parameters for Cd (II) biosorption by *Escherichia coli*. It compares pseudo-first order and pseudo-second order model fits, showing calculated adsorption capacities, rate constants, and correlation coefficients. The data indicate a better fit for the pseudo-first order model.

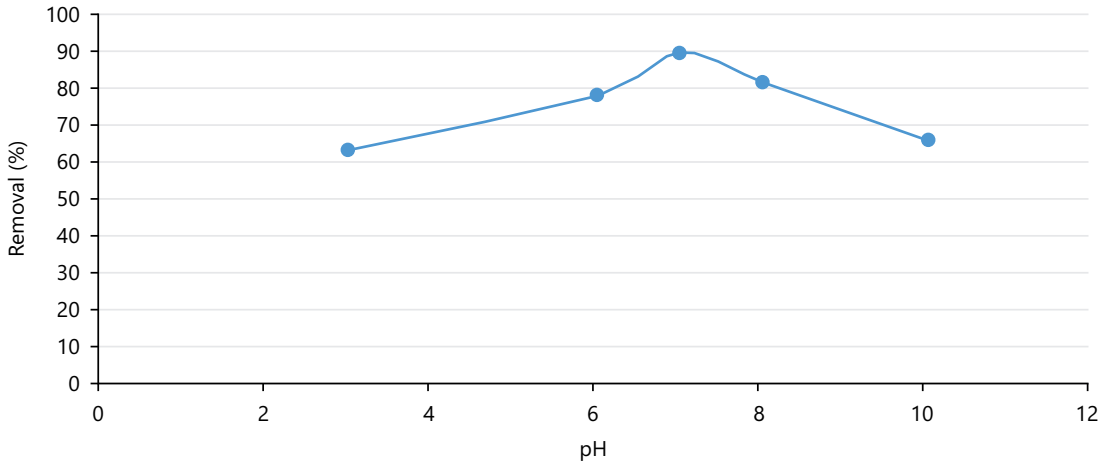

Fig. 4: Effect of pH on the biosorption of Cd ions by *Escherichia coli* isolated from a plastic recycling plant (Self-generated)

Effect of pH on Cd (II) biosorption by *Escherichia coli*. The curve shows percentage removal across pH values, with each point representing the mean of triplicate measurements

Table 2: Kinetic parameters for the biosorption of Cd ions by *Escherichia coli* isolated from a plastic recycling plant

Kinetic models	Cd (II)
$q_e$exp (mg/g)	48.83
Pseudo-first order	
$q_e$cal, (mg/g)	46.214
K_1, (min^{-1})	0.031
R^2	0.961
Pseudo-second order	
$q_e$cal, (mg/g)	30.21
K_2 (g/mg/min)	0.125
h (mg/g/min)	1.220
R^2	0.947

Kinetic model parameters for Cd (II) biosorption by *Escherichia coli*, Values include experimental and calculated qe, rate constants (K1, K2), initial sorption rate (h), and R^2 for each model

Table 3: Equilibrium isotherm parameters for the bio sorption of Cd ions by *Escherichia coli* isolated from a plastic recycling plant

Isotherm model	Cd (II)
Langmuir model	
q_L(mg/g)	50.013
K_L(L/mg)	0.210
R^2	0.924
Freundlich model	
K_F (L/g)	1.202
1/n	0.201
R^2	0.873

Equilibrium isotherm parameters for Cd (II) biosorption by *Escherichia coli*. Langmuir constants (qL, KL) and Freundlich constants (KF, 1/n) are shown with corresponding R^2 values

Isotherm modelling: Equilibrium data fitted best to the Langmuir model (high R^2), indicating monolayer adsorption on finite binding sites. Freundlich constants indicated heterogeneity consistent with biological sorbents (Table 3)[36].

Figure 4 depicts the effect of solution pH on Cd (II) biosorption, maximum uptake occurs at pH 7, with reduced adsorption at both acidic and alkaline extremes. This trend reflects the influence of proton competition and metal precipitation on biosorption efficiency.

Figure 5 presents the effect of initial Cd (II) concentration on biosorption capacity, Adsorption capacity increases with concentration until reaching a plateau, indicating sorbent saturation. This behaviour is characteristic of monolayer adsorption systems.

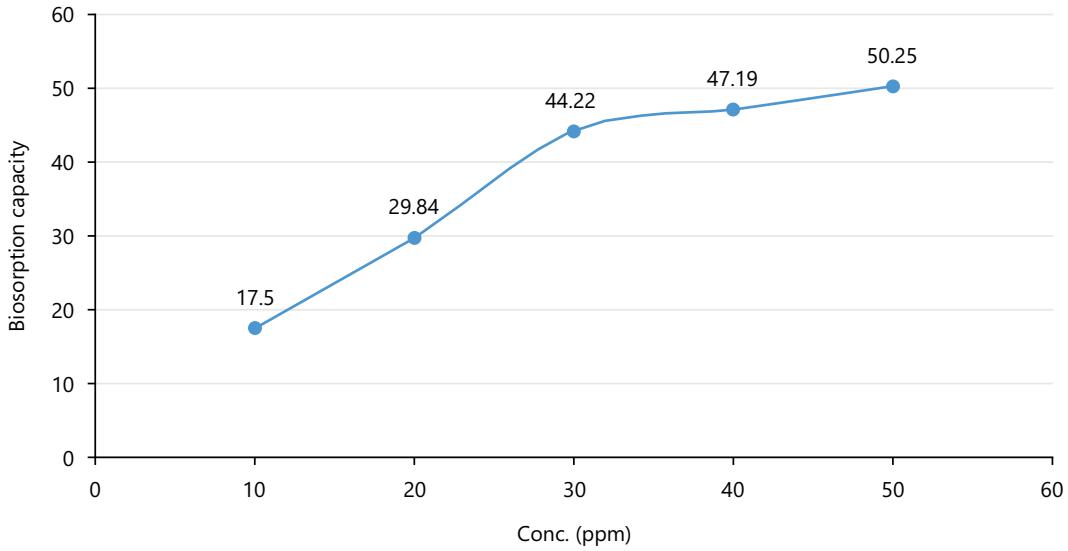

Fig. 5: Effect of Cd (II) ion concentration on the biosorption capacity of *Escherichia coli* isolated from a plastic recycling plant (Self-generated)

Effect of initial Cd (II) concentration on biosorption capacity of *Escherichia coli*. The plot shows qe values at varying concentrations, with data points representing mean triplicate results

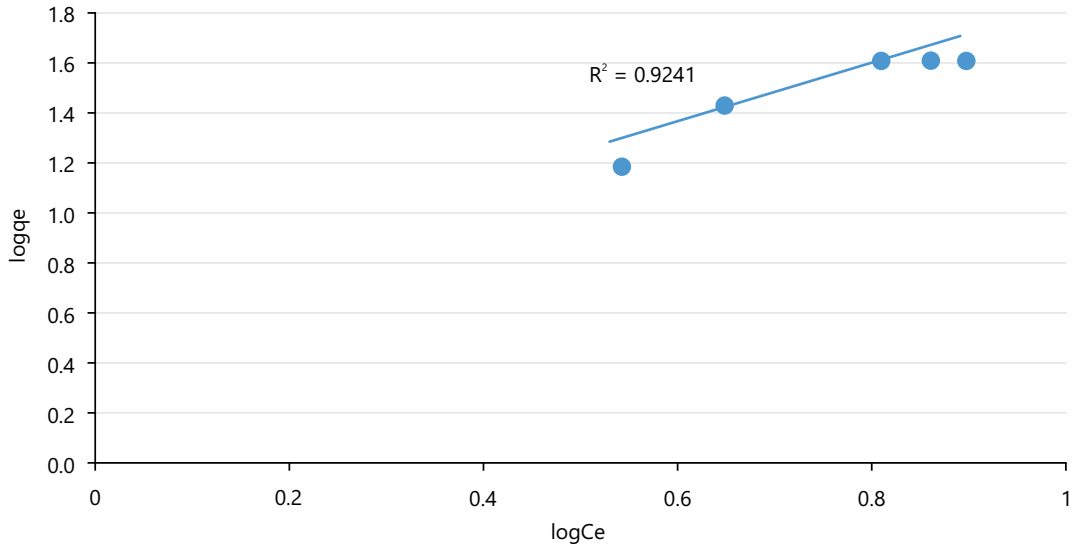

Fig. 6: Langmuir isotherm model plot for the biosorption of Cd (II) ions by *Escherichia coli* isolated from a plastic recycling plant (Self-generated)

Langmuir isotherm plot for Cd (II) biosorption by *Escherichia coli*. The graph displays logCe versus logqe, with the slope and intercept used to determine Langmuir constants

Figure 6 shows the Langmuir isotherm model plot for Cd (II) biosorption, The linear relationship supports the assumption of monolayer adsorption on homogeneous binding sites. The high correlation coefficient confirms the model's suitability.

Figure 7 illustrates the Freundlich isotherm model plot for Cd (II) biosorption The plot indicates surface heterogeneity and multilayer adsorption potential. Although the fit is slightly lower than Langmuir's, it provides complementary insight into sorption behaviour.

Table 3 summarises the Equilibrium isotherm parameters for Cd (II) biosorption, Langmuir constants indicate high monolayer adsorption capacity, while Freundlich constants suggest surface heterogeneity. The higher R^2 value for Langmuir confirms its superior fit to the experimental data.

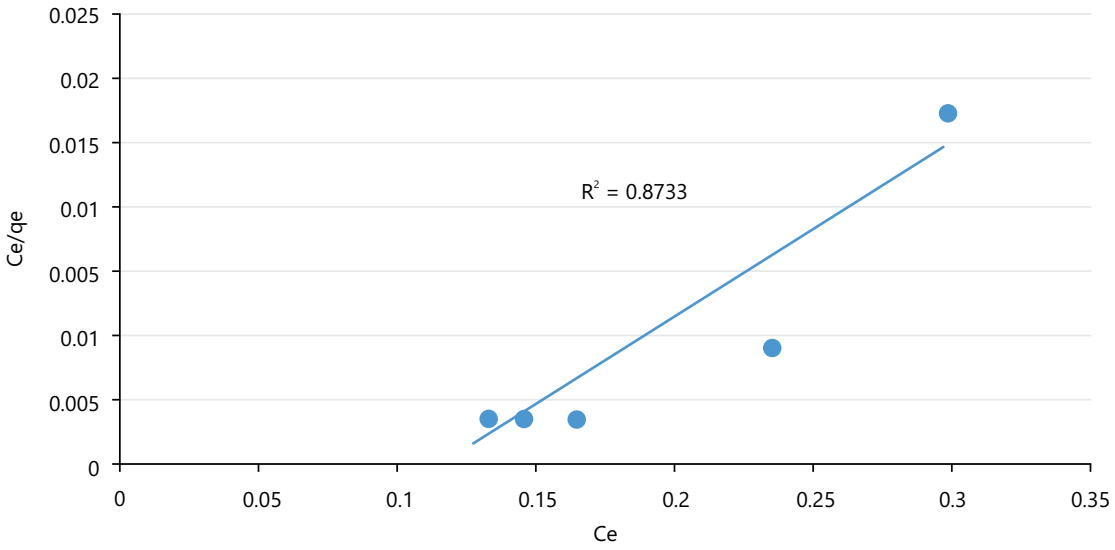

Fig. 7: Freundlich isotherm model plot for the bio sorption of Cd ions by *Escherichia coli* isolated from a plastic recycling plant

Freundlich isotherm plot for Cd (II) biosorption by *Escherichia coli*. The graph shows Ce/qe versus Ce, with slope and intercept used to calculate Freundlich constants

DISCUSSION

This study, evaluated the ability of Escherichia coli biomass, collected from a plastic recycling site, to remove Cd (II) from water. Experiments show a maximum adsorption capacity (q_m) of 50.013 mg/g, an optimum pH of about 7, and an approach to equilibrium within roughly 24 to 28 hrs. The equilibrium data fit a Langmuir-type isotherm and the kinetic behavior is best described by a pseudo-first-order model.

Cd (II) uptake is highest near neutral pH and declines at low pH fits well with the mechanistic picture reported by Patel[16] and others. Those authors show how pH controls metal speciation and the ionization state of surface functional groups, so proton competition at acidic pH naturally reduces available binding sites. Tran *et al.*[29] also caution that apparent increases in removal at high pH can sometimes reflect metal precipitation rather than true sorption. Taken together, these studies support our interpretation that pH 7 most reliably represents true biosorptive binding rather than an artifact of solution chemistry.

The kinetic profile we observed a rapid initial uptake over the first few hours followed by a slower approach to equilibrium, is consistent with many reports on microbial and plant-based sorbents. Bullen *et al.*[17] and Foo and Hameed[30] describe how an early, fast phase is often controlled by surface adsorption and film diffusion, while later uptake reflects intraparticle diffusion or site reorganization. Our data show a slightly better fit to a pseudo-first-order model, which plausibly indicates that physical adsorption and diffusion processes dominate under our conditions rather than exclusive chemisorption. This interpretation aligns with the kinetic analyses reported by Bullen *et al.*[17] and with broader reviews summarized by Foo and Hameed[30].

The equilibrium behavior favoring a Langmuir-type isotherm suggests monolayer adsorption on a finite number of relatively uniform sites. Similar Langmuir type fits have been reported for a variety of biological sorbents: Dias *et al.*[7] reported Langmuir behavior for nutshell-derived materials, and Zhang *et al.*[15] observed comparable fits for alginate-based composites. The q we measured, around 50 mg/g, places our *E. coli* biomass in a competitive range when compared with many low-cost sorbents. For example, Tatah *et al.*[10] report capacities for several agricultural residues in a similar range, and engineered biocomposites evaluated by Park *et al.*[14] and Zhang *et al.*[15] show comparable performance.

Practical trade-off commonly seen in batch sorption work: raising biomass dose increases total percent removal but can reduce adsorption per unit mass. Patel[16] and Foo and Hameed[30] explain this phenomenon as resulting from overlapping diffusion layers, reduced driving force per unit mass, and site aggregation at high sorbent loadings. These insights will guide how we scale the system: higher sorbent doses improve effluent quality but may be less efficient on a mass basis.

Sourcing biomass from a recycling site adds a sustainability dimension to our work. Fabre *et al.*[18] and Boakye *et al.*[19] advocate valorizing waste biomass for remediation, and our results show that such an approach can yield competent biosorbents. Recent reviews on bacterial biosorbents by Pham *et al.*[34] and Rizvi *et al.*[35] reinforce the idea that bacterial biomass can be scaled while reminding us to address regeneration, stability, and biosafety before field deployment.

There are methodological points to acknowledge. Tran *et al.*[29] remind us not to overinterpret model fits when relying only on linearized plots or R^2 values. We used both linear and nonlinear fitting approaches and reported error metrics, which strengthens confidence in our conclusions. Nevertheless, targeted follow up work would make our mechanistic claims more robust. I recommend thermodynamic studies, surface characterization by FTIR or XPS, and column-scale trials as suggested by Zhou *et al.*[25] to validate batch findings under continuous flow and in complex matrices. Multi-metal and real wastewater experiments will also be essential because competitive sorption can alter both capacity and selectivity.

In summary, our findings are consistent with established biosorption principles: pH dependence, rapid initial uptake with diffusion-limited equilibration, Langmuir type equilibrium behavior, and competitive q_m values. The novel contribution of this study is showing that *E. coli* biomass sourced from a recycling environment is a promising, low-cost biosorbent. Based on these results, column experiments, regeneration studies, and targeted surface analyses are being conducted to advance toward practical application.

CONCLUSION

This study confirms that *Escherichia coli* isolated from a plastic recycling plant demonstrates strong biosorption potential for Cd (II) ions under controlled laboratory conditions. Maximum removal efficiency was achieved at neutral pH, with equilibrium attained within 24-28 hrs. The biosorption behavior followed the Langmuir isotherm and pseudo-first-order kinetic models, indicating monolayer adsorption and a diffusion-driven mechanism. These results establish *E. coli* biomass as an effective and low-cost biosorbent for cadmium removal in wastewater treatment.

Further research should explore the regeneration and reuse potential of the biomass and conduct pilot-scale column experiments to evaluate performance under continuous flow conditions. Integrating this biosorbent into modular treatment systems may provide scalable and sustainable solutions for industrial effluents, particularly in resource-limited regions. Moreover, molecular-level investigations of metal-binding mechanisms would deepen understanding and support optimization for broader heavy metal remediation applications.

SIGNIFICANCE STATEMENT

Heavy metal contamination, particularly cadmium in water, remains a critical environmental and public health issue requiring affordable and sustainable remediation strategies. This study demonstrates that Escherichia coli biomass obtained from a plastic recycling site effectively removes Cd (II) ($q \approx 50.0$ mg/g), achieving optimal uptake at approximately neutral pH (≈7) with consistent kinetic and equilibrium performance. These findings highlight that waste-derived microbial biomass can perform comparably to other low-cost sorbents and can be readily integrated into existing treatment workflows. The proposed approach aligns with circular economy principles and offers a viable pathway toward pilot-scale testing, multi-metal evaluations, and deployment in resource-constrained environments.

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