Kinetic and Isotherm Equations to Calculate the Biosorption of Lead (Pb^{2+}) Ions from Aqueous Solutions by *Pseudomonas* spp

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Abstract

Lead (Pb^{2+}) contamination of water resources poses serious environmental and human health risks, and conventional physicochemical treatment methods are often costly and generate secondary waste. This study evaluated the biosorption of Pb^{2+} ions from aqueous solution using Pseudomonas spp. biomass as a low-cost, eco-friendly biosorbent. Batch kinetic experiments were carried out over 5–60 min at an initial Pb^{2+} concentration of 30 mg L^{-1} (298 K, 100 rpm), and equilibrium isotherm experiments were performed over an initial concentration range of 5–30 mg L^{-1} at 318 K. Kinetic data were analyzed using the pseudo-first-order (PFO) and pseudo-second-order (PSO) models, while equilibrium data were fitted to the Langmuir and Freundlich isotherms. The adsorption kinetics were best described by the PFO model (R^2 = 0.936; k1 = 0.1408 min^{-1}; qe = 136.55 mg g^{-1}), indicating a physisorption-controlled mechanism dominated by film diffusion, whereas the PSO model showed a much weaker fit (R^2 = 0.594). Equilibrium data deviated strongly from the Langmuir model (R^2 = 0.1631) but fitted the Freundlich model well (R^2 = 0.8215; KF = 3.58; 1/n = 0.89), consistent with a heterogeneous bacterial surface bearing multiple binding-site energies. The maximum theoretical Langmuir capacity was 149.25 mg g^{-1}, with a favorable separation factor (RL = 0.60–0.90). These results indicate that Pseudomonas spp. is an effective, low-cost biosorbent for Pb^{2+} removal from contaminated water and is a promising candidate for sustainable wastewater treatment applications.

Keywords: Biosorption, Physicochemical properties, Adsorption, Kinetic and adsorption isotherm.

Introduction

Heavy metal pollution has become one of the most persistent environmental problems associated with rapid industrialization and urban development. Among these toxic metals, lead (Pb^{2+}) is of particular concern because of its high toxicity, non-biodegradability, and strong tendency to bioaccumulate in living organisms [14]. Lead is commonly discharged into aquatic environments through mining operations, battery manufacturing, metal plating, pigment and paint industries, and chemical production [3]. Once released, Pb^{2+} ions can persist in water and sediments for extended periods, entering the food chain and causing chronic health problems in humans such as neurological disorders, renal dysfunction, anemia, and developmental impairment in children [6,18].

Conventional physicochemical methods for heavy metal removal—such as chemical precipitation, ion exchange, electrocoagulation, and membrane filtration—are often limited by high operational costs, the production of secondary sludge, and

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reduced efficiency at low metal concentrations [10,22]. Consequently, there is an increasing need for low-cost, eco-friendly, and sustainable technologies capable of efficiently removing lead and other heavy metals from contaminated water.

Biosorption, the passive binding of metal ions to biological materials (living or dead), has emerged as an effective and environmentally benign technique for metal removal [7,24,29]. This process exploits functional groups present on the surface of biomass—such as carboxyl, hydroxyl, phosphate, and amino groups—that interact with metal cations through mechanisms including ion exchange, complexation, electrostatic attraction, and microprecipitation [2,30]. Compared to traditional methods, biosorption offers advantages such as high metal uptake capacity, minimal generation of waste, and potential for biomass regeneration and reuse.

Among the various microorganisms explored as biosorbents, bacteria of the genus Pseudomonas have gained particular attention due to their ubiquity, metabolic versatility, and remarkable tolerance to heavy metals [2]. The cell wall of Pseudomonas contains peptidoglycan, lipopolysaccharides, and extracellular polymers rich in reactive sites capable of binding metal ions [28]. Previous studies demonstrated that Pseudomonas aeruginosa and related species can efficiently remove Pb(II), Cd(II), and other toxic ions under optimized conditions of pH, contact time, and biomass dosage [2,4,5,27].

To understand the mechanism of biosorption, researchers commonly employ kinetic models—such as the pseudo-first-order and pseudo-second-order equations—to describe the rate of metal uptake and identify the rate-controlling steps [12,13,25]. In addition, adsorption isotherm models, such as Langmuir and Freundlich, are applied to characterize the surface properties and maximum biosorption capacity of the biomass [8,20]. Typically, Pb (II) biosorption by Pseudomonas spp. has been found to follow the pseudo-second-order kinetic model and fit the Langmuir isotherm, suggesting monolayer adsorption on a homogenous surface [3].

Accordingly, this study aims to evaluate the biosorption performance of Pseudomonas spp. for the removal of Pb (II) ions from aqueous solutions. The research includes kinetic and equilibrium experiments to determine the rate and capacity of adsorption, the effects of operational parameters (such as pH, contact time, and initial metal concentration), and the application of kinetic and isotherm models to elucidate the underlying adsorption mechanisms. This approach will provide insights into the potential of Pseudomonas spp. as a sustainable biosorbent for heavy metal remediation and contribute to developing efficient, environmentally friendly wastewater treatment systems.

Materials and Methods

Bio Samples

Bacterial samples of Pseudomonas spp. were obtained and maintained under standard laboratory conditions prior to their use as the biosorbent material in the present study. The isolate was cultured on an appropriate growth medium, incubated under optimal temperature and aeration conditions, and identified using standard microbiological and biochemical procedures consistent with the characteristics of the genus Pseudomonas. A pure, actively growing culture was subsequently prepared and processed to obtain the biomass (denoted PS/SP) used in the biosorption experiments described below.

Preparation of Stock Solution for Pb^{2+} ion

The stock solution of Pb^{2+} ions was prepared by dissolving 1.6 grams of lead (II) nitrate ($Pb(NO_3)_2$) in 1000 mL of a 0.01 M sodium nitrate ($NaNO_3$) solution, resulting in a concentration of 1000 mg L^{-1}. The solution was then diluted to the desired concentrations, and the pH was adjusted using 0.1 M sodium hydroxide (NaOH) or hydrochloric acid (HCl).

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The percentage removal (R, %) of lead ions from the solution was calculated using the following equation, where Co and Ce are the initial and equilibrium concentrations of lead ions (mg L^{-1}), respectively:

$$R\ (\%) = (Co - Ce) / Co \times 100 \quad (1)$$

As for lead adsorbed per gram of SP (adsorption capacity), it was estimated using the following equation:

$$qe = (Co - Ce) \times V / M \quad (2)$$

Where: Ce: Concentration of lead ions after adsorption (mg L^{-1}). Co: Initial concentration of lead ions (mg L^{-1}). qe: Adsorption capacity of the adsorbent (mg g^{-1}). V: Volume of the solution (L). M: Mass of the adsorbent (g).

Adsorption studies

Kinetic equations: The kinetics of lead ion adsorption onto the surface of Pseudomonas spp. were investigated through a time-dependent adsorption experiment. In this experiment, 0.01 g of Pseudomonas spp. biomass was added to 40 mL of a neutral lead nitrate solution with an initial concentration of 30 mg L^{-1}. The mixtures were placed in volumetric flasks and shaken horizontally in a temperature-controlled water bath maintained at 298 K and 100 rpm.

At predetermined time intervals (5, 10, 15, 30, and 60 min), the suspensions were filtered to separate the bacterial biomass from the supernatant. The residual concentration of lead ions in the filtrate was determined using an atomic absorption spectrometer (AAS). The percentage removal of lead ions from the solution was calculated using Equation (1).

Kinetic models, including the pseudo-first-order and pseudo-second-order equations, were applied to the experimental data obtained from the equilibrium time determination in order to identify the model that best describes the adsorption mechanism of lead ions by Pseudomonas spp.

Pseudo-First Order Equation: the linear form of the equation is:

$$Ln(qe - qt) = Ln\ qe - K1\ t \quad (3)$$

Where: qe: Adsorption capacity at equilibrium (mg g^{-1}). qt: Adsorption capacity at time t (mg g^{-1}). K1: A constant representing the rate of the adsorption process (min^{-1}). By plotting Ln(qe − qt) against t, we obtain the curve for this equation [12,16,20].

Pseudo-Second Order Equation: the linear form of the equation is:

$$t/qt = 1/(K2\ qe^2) + (1/qe)\ t \quad (4)$$

Where: K2: The constant of the equation representing the rate of adsorption (g mg^{-1} min^{-1}). By plotting t/qt against t, we obtain the curve for this equation [13,20].

Adsorption isotherm

The optimal initial concentration for the adsorption of lead ions onto the surface of Pseudomonas spp. was determined by adding 0.01 g of bacterial biomass to 40 mL of neutral lead nitrate solutions with different initial concentrations (5, 10, 15, 20, and 30 mg L^{-1}). The flasks were placed on a horizontal shaker in a temperature-controlled water bath maintained at the optimal temperature of 318 K and agitated at 100 rpm for equilibrium time.

After shaking, the suspensions were filtered to separate the bacterial biomass from the supernatant, and the residual concentration of lead ions in the filtrate was determined using an atomic absorption spectrometer (AAS). The percentage removal of lead ions from the solution was calculated using Equation (1).

Adsorption isothermal models and curves were applied to the experimental data obtained from the optimal initial concentration determination experiment. By plotting the adsorption capacity values (qe), estimated using Equation (2), against the equilibrium concentrations of lead ions (Ce), the adsorption isotherm curve was obtained and

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further analyzed to identify the model that best fits the experimental data.

The Langmuir isotherm equation: the linear form of the Langmuir equation is as follows:

$$Ce/qe = 1/(qm.KL) + Ce/qm \quad (5)$$

Where: qe: The amount of adsorbate at equilibrium (mg g^{-1}). Ce: The concentration of the adsorbate at equilibrium (mg L^{-1}). qm: The maximum adsorption (mg g^{-1}). KL: The Langmuir equation constant. By plotting Ce/qe against Ce, we obtained the curve of the equation, and the values of (qm and KL) were estimated from the slope and intercept of the curve [8,17]. The relative equilibrium constant (RL) was calculated using the equation:

$$RL = 1 / (1 + KL\ Co) \quad (6)$$

The Freundlich isotherm equation: the linear form of the Freundlich equation is as follows:

$$Log\ qe = Log\ KF + (1/n)\ Log\ Ce \quad (7)$$

Where: KF: A constant that represents the adsorption capacity. n: A constant that represents the suitability of the adsorption process. The constants were estimated from the slope and intercept of the curve [8,9].

Results and Discussion

Kinetics of Adsorption — Pseudo-First Order Model

Figure (1) shows the curve of the equation. From the slope and intercept of the straight line, the constants K1 and qe were calculated.

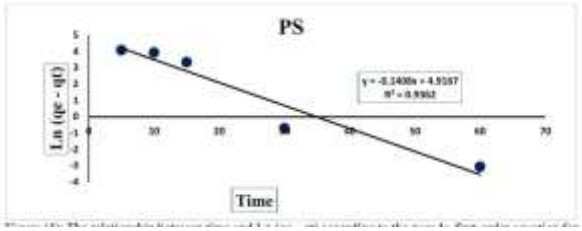


Figure 1: The relationship between time and Ln(qe − qt) according to the pseudo-first-order equation for the adsorption of lead ions on PS (initial Pb^{2+} concentration 30 mg L^{-1}, 298 K, 100 rpm).

Pseudo-Second Order Model

Figure (2) illustrates the equation curve, and from the slope and intercept of the straight line, the constants K2 and qe were calculated.

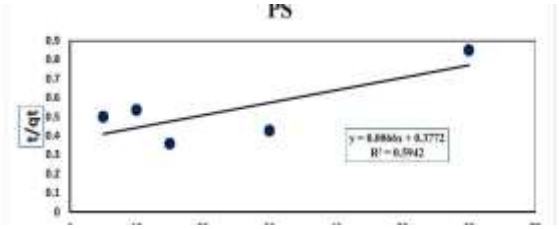


Figure 2: The relationship between time and (t/qt) according to the pseudo-second-order equation for the adsorption of lead ions on PS (initial Pb^{2+} concentration 30 mg L^{-1}, 298 K, 100 rpm).

The adsorption kinetics of Pb (II) onto the Pseudomonas sp. biomass were evaluated using the pseudo-first order (PFO) and pseudo-second order (PSO) models. The kinetic data exhibited an excellent agreement with the PFO model (R^2 = 0.9362), while the PSO model showed a substantially lower correlation (R^2 = 0.5942). The superior fit of the PFO model indicates that the adsorption mechanism is predominantly governed by physisorption, where the rate depends on the difference between the equilibrium capacity (qe) and the amount adsorbed at time t (qt), as originally described by Lagergren (1898) [12,16]. The calculated kinetic parameters for the PFO model (k1 = 0.1408 min^{-1}; qe = 136.55 mg·g^{-1}) confirm a rapid initial uptake phase, reflecting the accessibility of active surface sites on the bacterial biomass. In contrast, the PSO model yielded inconsistent qe values (151.52 mg·g^{-1}) and a very low rate constant (k2 = 1.15×10^{-4} g·mg^{-1}·min^{-1}), suggesting that chemisorption is not the rate-limiting step in this system. The kinetic parameters obtained from the two models are summarized in Table 1.

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These findings are consistent with the broader literature on biosorption kinetics, which indicates that PFO behavior frequently dominates in systems involving bacterial, algal, and biochar-based materials, and is commonly associated with weak surface interactions and film diffusion control [19,21]. A closely related case is the Gram-negative bacterium Chelatococcus sp., for which Pb(II) biosorption was also best described by the pseudo-first-order model, in agreement with the present results [5].

In addition, reviews of adsorption kinetic models emphasize that systems dominated by external mass transfer and weak binding energies typically conform more strongly to the PFO rate law, with PFO generally associated with physisorption or surface-reaction control and PSO more often linked to chemisorption or intraparticle diffusion [20,21]. It should be emphasized that PFO and PSO are empirical rate equations: the apparent reaction order depends on experimental conditions such as the initial sorbate concentration [1], and a higher correlation coefficient for one model does not by itself prove a specific rate-controlling mechanism [23,25].

Overall, the dominance of the PFO model suggests that Pb(II) adsorption onto the Pseudomonas biomass is governed mainly by surface-controlled interactions—particularly film diffusion and weak electrostatic forces—rather than covalent chemical bonding. This mechanism may be further validated by intraparticle diffusion modeling (Weber–Morris), which is recommended for future investigations.

Table 1: Kinetic parameters (K, Qe and R^2) of the pseudo-first-order and pseudo-second-order equations for the adsorption of lead ions on PS (Qe (laboratory): experimentally measured adsorption capacity).

Equation	Parameter	PS
—	Qe (laboratory)	70.64
Pseudo-First Order Model	K1	0.1408
Pseudo-First Order Model	Qe	136.55
Pseudo-First Order Model	R^2	0.9362
Pseudo-Second Order Model	K2	1.15×10^{-4}
Pseudo-Second Order Model	Qe	151.52
Pseudo-Second Order Model	R^2	0.5942

The Adsorption Isotherm

Figure (3) illustrates the adsorption curves of lead ions on SP.

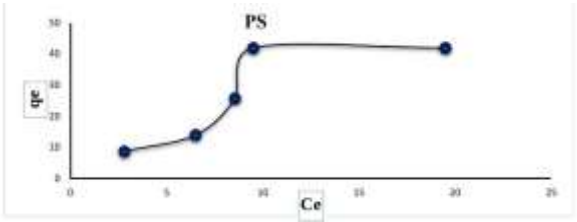


Figure 3: Adsorption isotherm curve (qe versus Ce) of lead ions on SP surfaces (initial Pb^{2+} concentrations 5–30 mg L^{-1}, 318 K, 100 rpm).

The adsorption isotherms obtained for Pb(II) removal by Pseudomonas sp. exhibited an S-type pattern [11], a behavior typically associated with cooperative adsorption as the metal concentration increases. A low adsorption capacity was observed at low Pb(II) concentrations, consistent with the limited availability of bacterial binding sites at early stages of adsorption due to competition with water molecules [24]. As the concentration increased, the adsorption capacity rose sharply, indicating a gradual enhancement in the ability of the cells to bind Pb(II) ions. This trend is supported by studies on the role of exopolysaccharides (EPS) in improving the metal-binding capability of Pseudomonas on the cell surface [2,26]. At higher concentrations, the

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isotherm reached a plateau, indicating saturation of the available adsorption sites, consistent with kinetic and thermodynamic descriptions of metal biosorption by Pseudomonas species [3].

Overall, these findings confirm that Pseudomonas sp. exhibits high efficiency in Pb(II) removal at moderate and high concentrations, while showing relatively limited performance at low concentrations—an outcome that aligns with current research trends in the field of heavy-metal biosorption.

Langmuir Isotherm

Figure (4) illustrates the Langmuir isotherm for the adsorption of lead ions on SP surfaces.

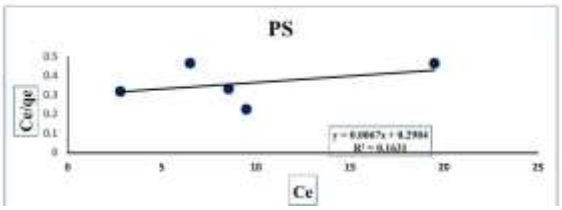


Figure 4: Langmuir isotherm (Ce/qe versus Ce) for the adsorption of lead ions on SP surfaces (initial Pb^{2+} concentrations 5–30 mg L^{-1}, 318 K, 100 rpm).

The Langmuir model was applied to evaluate the adsorption behavior of lead ions onto the surface of Pseudomonas sp. A linear relationship between Ce/qe and Ce showed a weak correlation, with a determination coefficient of R^2 = 0.1631, indicating that the Langmuir model does not accurately describe the adsorption mechanism in this case. This deviation is attributed to the heterogeneous nature of the bacterial surface, which contradicts the Langmuir assumptions of uniform adsorption sites and monolayer formation [8,15,17].

Despite the poor model fit, the Langmuir constants derived (Table 2) provide important insights into the process. The theoretical maximum adsorption capacity (qm) was 149.25 mg/g, suggesting a high potential for lead removal from the solution. The Langmuir constant (KL = 0.0225 L/mg) reflects a relatively low affinity between lead ions and the functional groups on the Pseudomonas sp. surface, consistent with the role of carboxyl and hydroxyl groups on the cell wall in enhancing heavy metal binding [2,26].

The separation factor (RL = 0.60–0.90 for initial concentrations of 30–5 mg L^{-1}), which falls within the range of 0–1, indicates that the adsorption process is favorable under the studied concentration conditions. However, the significant deviation from the Langmuir model reflects that the adsorption mechanism is governed by heterogeneous surface interactions and possibly cooperative effects. These findings align with the broader literature showing that bacterial surfaces, due to the diversity of functional groups and the presence of extracellular polymers, often deviate from the traditional Langmuir model [15,21].

Overall, the results demonstrate that the Langmuir model is insufficient for accurately describing the adsorption behavior of Pseudomonas sp., and that the adsorption process involves more complex mechanisms, including surface heterogeneity and cooperative interactions, consistent with the S-type isotherm patterns observed previously.

Table 2: Langmuir constants (qm, KL, RL and R^2) for the adsorption of lead ions on SP surfaces.

Parameters	SP
qm	149.25
KL	0.0225
RL	0.60–0.90
R^2	0.1631

Freundlich Isotherm

Figure (5) illustrates the Freundlich isotherm for the adsorption of lead ions on SP surfaces.

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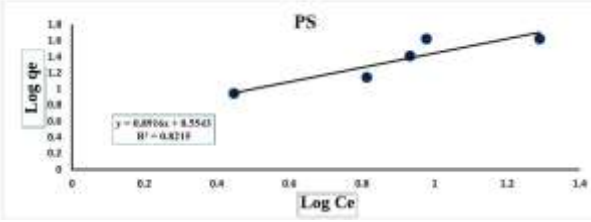


Figure 5: Freundlich isotherm (Log qe versus Log Ce) for the adsorption of lead ions on SP surfaces (initial Pb^{2+} concentrations 5–30 mg L^{-1}, 318 K, 100 rpm).

The results of the adsorption study demonstrated that Pseudomonas (Ps) exhibits a significant ability to remove lead ions from aqueous solutions. The data obtained from the Freundlich isotherm model showed a good fit between the experimental results and the theoretical model, as indicated by the correlation coefficient R^2 = 0.8215. This suggests that the adsorption process occurs on a heterogeneous surface with multiple adsorption sites of varying energies, consistent with the biological nature of bacterial surfaces rich in functional groups. The Freundlich constants are listed in Table 3.

The presence of active functional groups such as carboxyl, phosphate, hydroxyl, and amine groups on the bacterial cell surface or within the extracellular polysaccharides (EPS) explains the strong ability of the bacteria to bind and immobilize lead ions. These groups act as effective ligands that interact with lead through surface adsorption, complex formation, and ion exchange processes. This mechanism is consistent with the literature confirming the role of EPS in heavy metal binding, particularly in different Pseudomonas species isolated from various environments [2,26].

The adsorption intensity value 1/n = 0.89 (0 < 1/n < 1) indicates that the process is favorable, and that the bacterial surface contains a wide range of active sites capable of interacting with different concentrations of lead. Moreover, the Freundlich constant KF = 3.58 reflects the ability of the bacteria to retain lead at low to moderate concentrations, which aligns with the performance reported for several Pseudomonas strains previously used in heavy metal bioremediation.

Overall, these results suggest that Ps bacteria possess an effective capacity for the biosorption of lead and that their behavior closely aligns with published data on other Pseudomonas species. This supports the potential application of Ps in wastewater treatment and environmental remediation of lead-contaminated sites.

Table 3: Freundlich constants (KF, 1/n and R^2) for the adsorption of lead ions on SP surfaces.

Parameters	SP
KF	3.58
1/n	0.89
R^2	0.8215

Conclusions

This study demonstrated that Pseudomonas spp. biomass is an effective biosorbent for the removal of Pb^{2+} ions from aqueous solution. The kinetic data were best described by the pseudo-first-order model (R^2 = 0.936), indicating that the adsorption process is governed predominantly by physisorption and film diffusion rather than chemisorption, with rapid initial uptake reflecting good accessibility of surface binding sites. Equilibrium data deviated substantially from the Langmuir model (R^2 = 0.163) but were well described by the Freundlich model (R^2 = 0.8215; KF = 3.58; 1/n = 0.89), confirming that the bacterial surface is heterogeneous and offers multiple adsorption sites of varying binding energy, consistent with the S-type isotherm pattern observed and with cooperative adsorption behavior at higher lead concentrations.

Overall, the biomass exhibited high removal efficiency at moderate-to-high Pb^{2+}

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concentrations and a theoretical maximum capacity of 149.25 mg g^{-1}, supporting its potential as a low-cost, eco-friendly alternative to conventional physicochemical treatment methods for lead-contaminated wastewater. Future work should include intraparticle diffusion modeling (Weber–Morris) to further resolve the rate-controlling steps, thermodynamic analysis (ΔG°, ΔH°, ΔS°) to characterize the spontaneity and nature of the process, surface characterization (FTIR, SEM-EDX) to directly identify the functional groups and morphological changes involved in Pb^{2+} binding, and desorption/regeneration studies to assess the reusability of the biomass for practical wastewater treatment applications.

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