

Biosorption of Pb²⁺ Ions Using Immobilized Green Algae Biomass *Spirogyra setiformis* with Sodium Silicate

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ABSTRACT

This study aims to evaluate the adsorption performance of immobilized green algae *Spirogyra setiformis* biomass using sodium silicate as a biosorbent for the removal of Pb²⁺ ions from aqueous solutions. The investigated variables include pH, initial metal ion concentration, flow rate, and the influence of Cd²⁺ ion coexistence. The experiments were conducted using a column method, in which 1 g of biosorbent was contacted with Pb²⁺ solutions under various conditions. The analytical results revealed that optimum biosorption occurred at pH 5, achieving an adsorption capacity of 3.67 mg/g. The optimum initial concentration was found to be 300 ppm with an adsorption capacity of 6.87 mg/g, while the optimum flow rate of 20 drops/min resulted in a capacity of 6.92 mg/g.

INTRODUCTION

The rapid expansion of modern industries has led to a significant increase in wastewater discharge into the environment without adequate treatment. Among the major pollutants in industrial effluents are heavy metals such as lead (Pb^{2+}) and cadmium (Cd^{2+}), which are toxic, non-biodegradable, and easily accumulated within living organisms. Heavy metal contamination poses serious threats to aquatic ecosystems and human health. According to the Indonesian Government Regulation (2022), the maximum allowable concentrations of Pb^{2+} and Cd^{2+} in water are 0.03 mg/L and 0.01 mg/L, respectively. Exceeding these limits can cause organ damage, neurological disorders, and even mortality in aquatic biota.

Conventional methods for treating heavy metal pollution include chemical precipitation, ion exchange, and membrane technology. However, these techniques often suffer from limitations in terms of cost, efficiency, and sustainability. As an alternative, biosorption has emerged as an environmentally friendly, cost-effective, and efficient approach. This process utilizes biomasses containing active functional groups such as hydroxyl, carboxyl, and amine to bind metal ions through ion exchange, complexation, and physical adsorption mechanisms.

Green algae (*Chlorophyta*) represent one of the most promising biomasses for biosorption due to their abundance and cell wall composition rich in functional groups. *Spirogyra setiformis* is a filamentous green alga commonly found in freshwater environments and is known for its strong affinity toward heavy metal ions. However, the use of free biomass is often constrained by its low mechanical stability and difficulties in separation after biosorption.

To overcome these limitations, biomass immobilization using sodium silicate was applied. Immobilization enhances the physical stability of the biosorbent, prevents biomass degradation, and enables repeated use. Therefore, this study aims to evaluate the effectiveness of immobilized *Spirogyra setiformis* in adsorbing Pb^{2+} ions, determine the optimum biosorption conditions, assess the influence of Cd^{2+} ion coexistence, and test the biosorbent performance on actual wastewater samples.

LITERATURE REVIEW

Green Algae (Spirogyra Setiformis)

Green algae represent a promising biomass for use as a biosorbent due to their cell walls being rich in polysaccharides, proteins, and glycoproteins that contain active functional groups such as carboxyl ($-COOH$), hydroxyl ($-OH$), amine ($-NH_2$), and sulfate ($-SO_4H$). These functional groups play a crucial role in interacting with heavy metal ions through ion exchange, complexation, and adsorption mechanisms. *Spirogyra setiformis* is a filamentous green alga characterized by its spiral chloroplasts and is commonly found in freshwater environments. This biomass has been widely investigated for its high adsorption capacity toward various heavy metals, including Pb^{2+} and Cd^{2+} . However, the use of free biomass often encounters limitations such as low mechanical stability and difficulties in separation after the biosorption process.

Amaro et al. (2022), in *Environmental Technology & Innovation*, reported that the protein-rich cellular structure of algae plays a significant role in Pb^{2+} binding through weak covalent interactions with amine groups. This finding indicates that biosorption by algal biomass is a combination of chemical and physical mechanisms that are strongly influenced by environmental factors, particularly pH and temperature.

Recent studies have shown that the use of microalgae as biosorbents for heavy metals offers broad potential due to their complex and multifunctional adsorption mechanisms. According to Chugh et al. (2022) in *Algal Bioremediation of Heavy Metals: An Insight into Removal Mechanisms, Recovery of By-products, Challenges, and Future Opportunities (Energy Nexus)*, biosorption by algae involves not only electrostatic interactions but also coordination complex formation and ion exchange on active functional groups such as $-COOH$, $-OH$, and $-NH_2$. The article emphasizes that algal biomass can effectively remove Pb^{2+} ions even at low concentrations, achieving higher efficiency than conventional methods such as chemical precipitation or synthetic ion exchange. These findings reinforce the theoretical foundation of this study, which utilizes *Spirogyra setiformis* as a natural biosorbent for heavy metal remediation.

Furthermore, Karnib et al. (2014) in *Heavy Metals Removal Using Activated Carbon, Silica, and Silica-Activated Carbon Composite (Energy Procedia)* demonstrated that silica-based materials play an important role as structural supports in adsorption systems. The combination of hydroxyl groups ($-Si-OH$) on silica with organic functional groups from biomass produces a porous and stable surface, thereby enhancing the Pb^{2+} adsorption rate. These findings are consistent with the immobilization approach employed in this study, where sodium silicate serves as a reinforcing matrix for *Spirogyra setiformis* biomass. This matrix not only strengthens the structural integrity of the biosorbent but also improves its thermal stability and regeneration capability after multiple reuse cycles.

Biosorption

Biosorption is a metal ion uptake process that utilizes living or dead biomass as a biosorbent. The biosorption mechanism involves various physicochemical interactions, including surface adsorption, ion exchange, complexation, and micro-precipitation. Compared to conventional treatment methods, biosorption offers several advantages such as lower operational costs, environmental friendliness, and high efficiency in removing metals even at low concentrations.

In addition, the flow rate and contact time are critical parameters in continuous column systems. At higher flow rates, ion diffusion to active sites becomes restricted, leading to a decrease in adsorption efficiency. This phenomenon aligns with findings from previous studies showing that the optimal flow rate occurs under moderate conditions (20 drops per minute), where the residence time is sufficient to achieve adsorption equilibrium.

Biomass Immobilization with Sodium Silica

Immobilization is a technique used to entrap biomass within a supporting matrix, such as sodium silicate, to enhance its stability and facilitate separation after the biosorption process. Sodium silicate forms a porous gel that protects the biomass from degradation while maintaining the accessibility of functional groups for metal ion binding. Previous studies have shown that immobilized algal biomass exhibits greater durability and reusability in cyclic systems compared to free biomass. This makes immobilization an essential strategy for improving the performance and practicality of biosorbents in real-world applications.

HSAB (Hard and Soft Acid and Bases)

The Hard and Soft Acids and Bases (HSAB) theory explains the tendency of interactions between metal ions (acids) and the functional groups present in biomass (bases). Pb^{2+} is classified as a soft to borderline acid, which exhibits a strong affinity for soft base groups such as $-NH_2$ or other polar functional groups located on the algal cell wall. This characteristic supports the utilization of *Spirogyra setiformis* as a biosorbent, as its functional groups are chemically compatible with the nature of Pb^{2+} ions.

Environmental factors and the complexity of real wastewater also have a significant impact on biosorption effectiveness. According to Ordonez et al. (2023) in "*Biosorption of Heavy Metals with Algae: Critical Review of Its Application in Real Effluents*" published in *Sustainability*, many laboratory studies have reported optimal biosorption performance under controlled conditions; however, when applied to real effluents, the efficiency often decreases due to ion competition particularly from Ca^{2+} , Na^+ , and Mg^{2+} as well as pH fluctuations. The article emphasizes the importance of a comprehensive understanding of wastewater characteristics and the adaptive capacity of biomass under real environmental conditions. This is directly relevant to the present study, which employs laboratory wastewater as a test sample to evaluate the performance of immobilized biosorbents in a more complex environment.

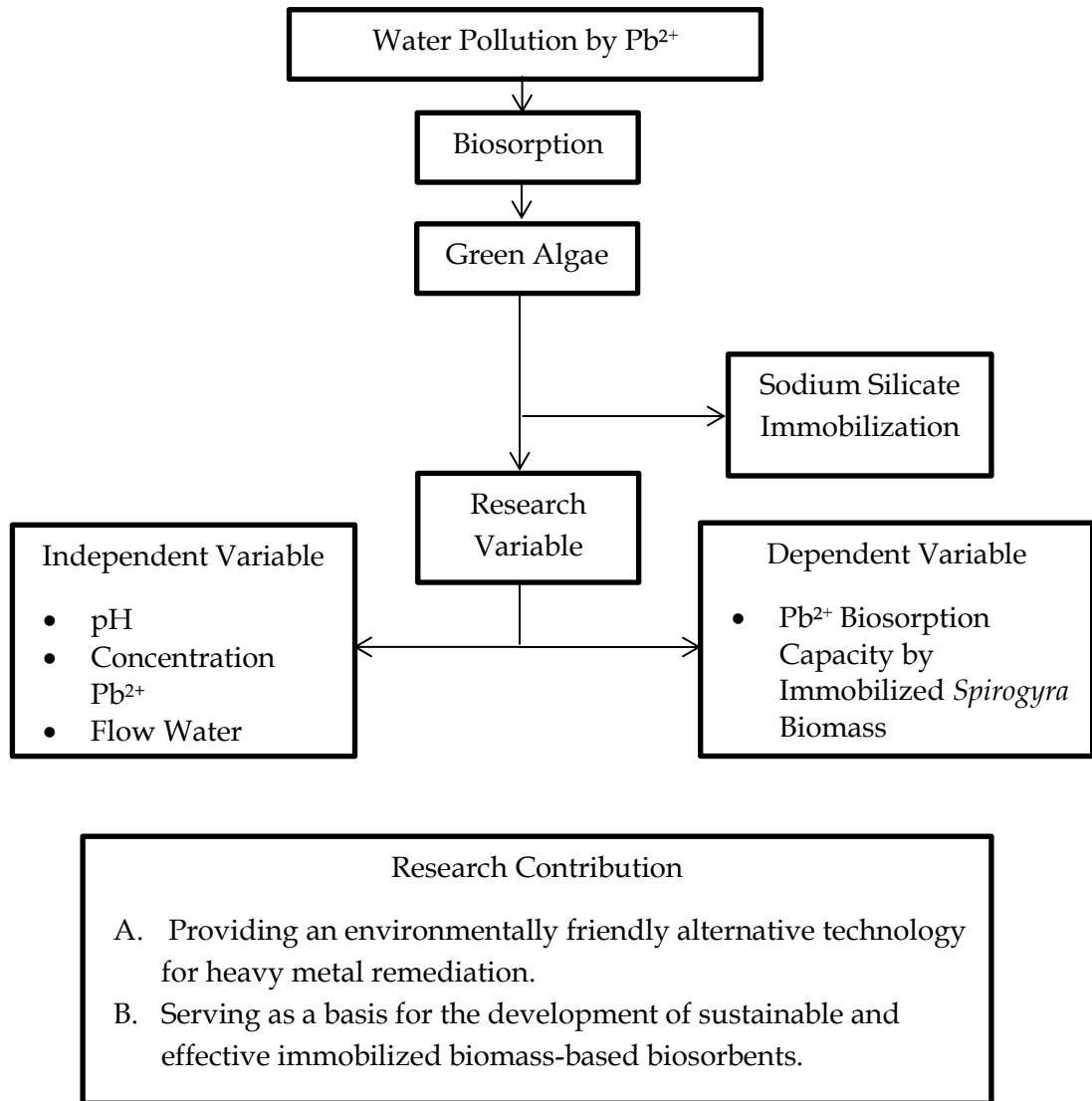


Figure 1. Conceptual Framework

METHODOLOGY

This research was conducted at the Research Laboratory of the Faculty of Mathematics and Natural Sciences, Universitas Negeri Padang, and the Laboratory of LLDIKTI Region X Padang during the period of May–August 2025. The study focused on the biosorption of Pb²⁺ ions using immobilized green algae *Spirogyra setiformis* biomass with sodium silicate as the immobilizing agent. The research population consisted of liquid waste containing heavy metal ions, while the samples used included standard Pb²⁺ solutions prepared in the laboratory and actual wastewater collected from the LLDIKTI Region X Laboratory in Padang.

The experimental variables consisted of independent variables (pH, initial concentration, and flow rate), a dependent variable (biosorption capacity of Pb²⁺), and a control variable (the *Spirogyra setiformis* biosorbent). The study employed a column method in which the biosorbent was packed into a glass column and continuously passed with metal ion solutions under varying pH, concentration, and flow rate conditions.

The experimental procedure included the following stages: (1) preparation of *Spirogyra setiformis* biomass through washing, drying, grinding, and acid treatment; (2) immobilization of the biomass using sodium silicate to enhance mechanical stability; (3) biosorption experiments of Pb²⁺ ions under variations of pH, concentration, and flow rate; (4) evaluation of biosorbent reusability through adsorption-desorption cycles; and (5) application of the biosorbent to actual wastewater samples to assess its effectiveness. The concentration of metal ions after biosorption was determined using an Atomic Absorption Spectrophotometer (AAS), while the functional groups of the biosorbent were characterized using Fourier Transform Infrared Spectroscopy (FTIR). The obtained data were analyzed to determine the maximum adsorption capacity, optimum biosorption conditions, and the stability of the biosorbent upon repeated use.

RESEARCH RESULTS

Identification of Green Algae Sample

The green algae sample collected from the Lintau Buo River was successfully identified as *Spirogyra setiformis* based on its morphological characteristics, which include long filamentous structures with spiral chloroplasts. This identification confirmed that the biomass utilized in this study corresponded to the intended target species (Figure 2).

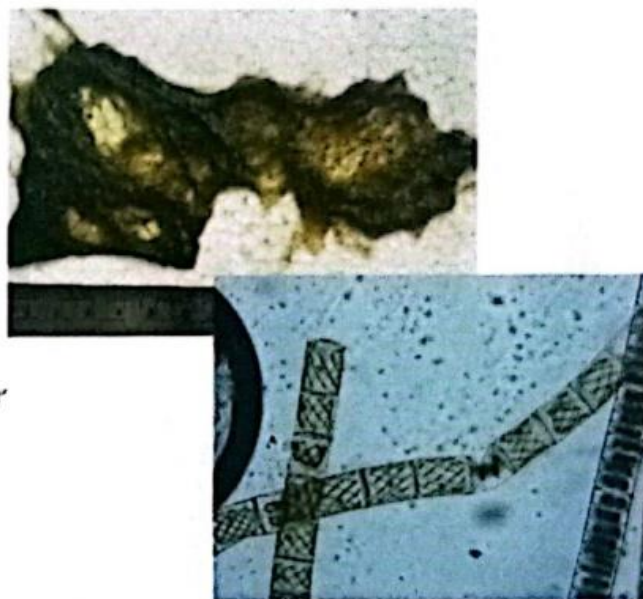


Figure 2. The Microscopic Identification was Carried Out Using a Light Microscope at the Biology Laboratory, Andalas University (UNAND)

Characterization of Biomass Functional Groups

FTIR analysis revealed the presence of characteristic absorption bands in the immobilized green algal biomass, including shifts in the -OH and Si-O bands, indicating the successful immobilization process using sodium silicate. In addition, carboxyl and amine bands were observed, which play a crucial role in Pb^{2+} ion binding. The changes in band intensity and position after the biosorption process further confirmed the involvement of these functional groups in metal ion interactions (Figure 3).

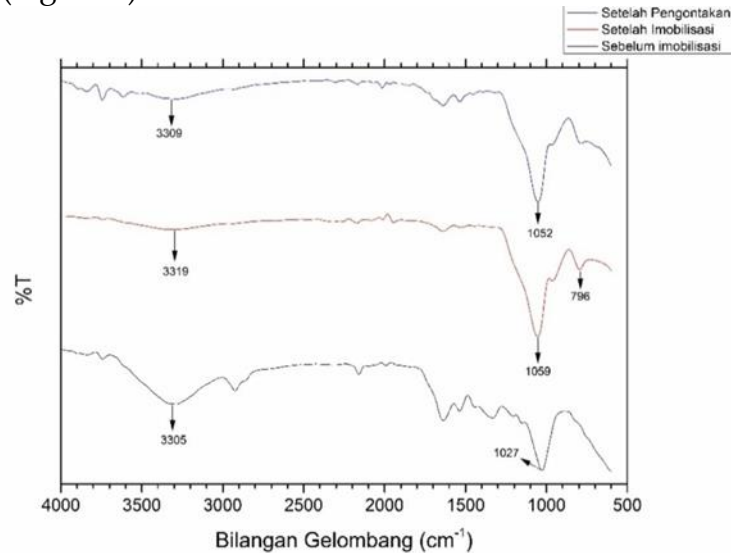


Figure 3. FTIR Spectra of Green Algae Biomass Before Immobilization, After Immobilization with Sodium Silicate, and After Contact With Pb^{2+} Solution

Effect of pH

The experimental results indicated that the Pb^{2+} ion adsorption capacity was strongly influenced by the solution pH. The optimum biosorption occurred at pH 5, with an adsorption capacity of 3.67 mg/g. At lower pH values (<4), protonation of the active sites hindered the interaction between Pb^{2+} ions and the biosorbent, whereas at higher pH levels, the possible precipitation of metal ions as hydroxides reduced the overall biosorption efficiency (Figure 4).

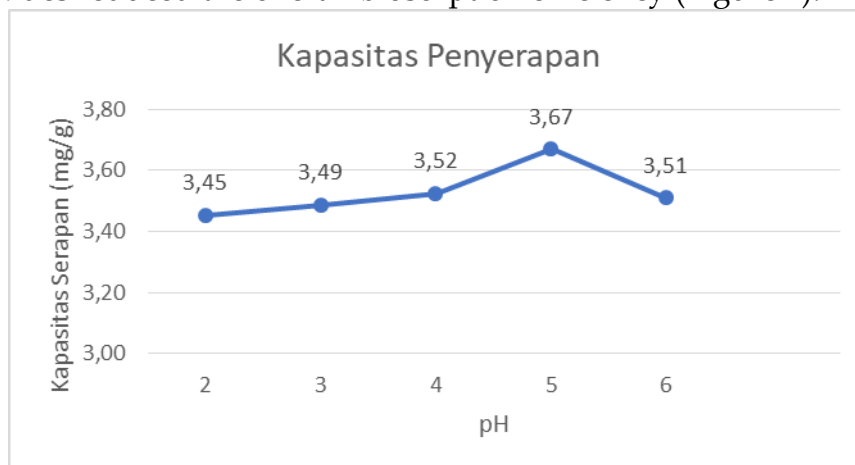


Figure 4. Effect of Initial Ph of Pb^{2+} Ions on the Biosorption Efficiency of Immobilized Green Algae Biosorbent

Effect of Initial Concentration

The adsorption capacity increased with the rise in the initial Pb^{2+} ion concentration, reaching an optimum at 300 ppm with a maximum capacity of 6.87 mg/g. Beyond this concentration, the adsorption capacity decreased due to the saturation of active binding sites on the biosorbent surface. The Langmuir isotherm model provided the best fit to the experimental data, with a determination coefficient (R^2) close to 1, indicating that the biosorption process followed a monolayer adsorption mechanism (Figure 5).

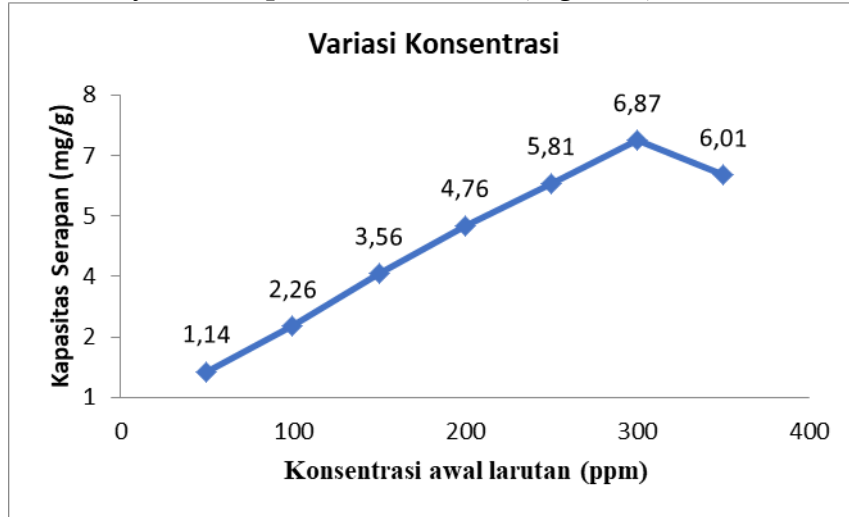


Figure 5. Effect of Initial Pb^{2+} Ion Concentration on the Biosorption Capacity of Immobilized Green Algae Biosorbent

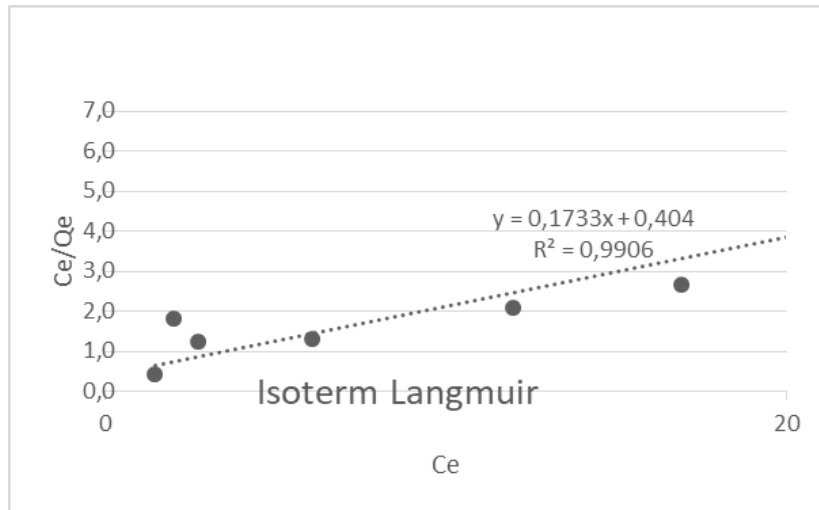


Figure 6. Langmuir Isotherm Curve Describing the Adsorption Behavior of Pb^{2+} Ions on the Immobilized Green Algae Biosorbent

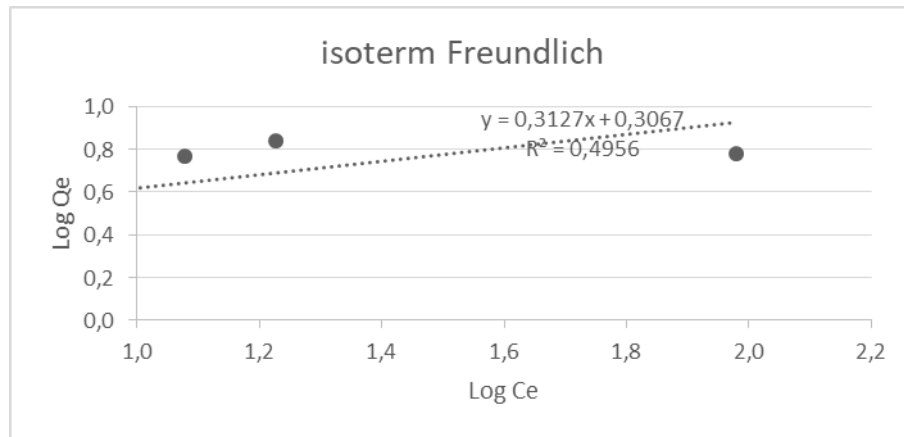


Figure 7. Freundlich Isotherm Curve Describing the Adsorption Behavior of Pb²⁺ Ions on the Immobilized Green Algae Biosorbent

Effect of Flow Rate

The flow rate also influenced the biosorption capacity. At a rate of 20 drops per minute, the maximum adsorption capacity was achieved at 6.92 mg/g. Higher flow rates resulted in shorter contact times, thereby decreasing biosorption efficiency due to the limited opportunity for Pb²⁺ ions to interact with the active sites of the biosorbent (Figure 8).

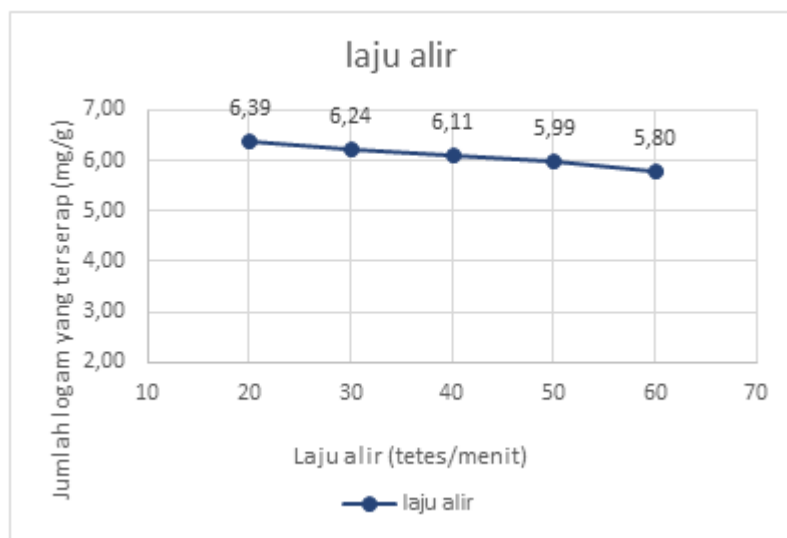


Figure 8. Effect of Flow Rate on the Biosorption of Green Algae Biosorbent

Effect of Cd²⁺ Ions

The results indicated competition between Pb²⁺ and Cd²⁺ ions at the active sites of the biosorbent. The presence of Cd²⁺ reduced the biosorption capacity of Pb²⁺ from 6.92 mg/g to 3.12 mg/g at a specific ratio. This suggests that Cd²⁺ exhibits a relatively high affinity toward the functional groups of the algae, thereby decreasing the amount of Pb²⁺ that can be adsorbed (Figure 9).

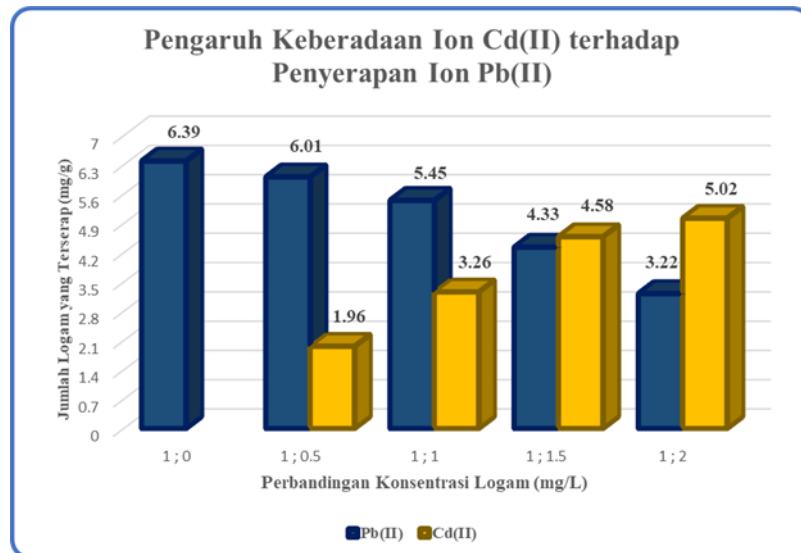


Figure 9. Effect of Cd²⁺ Ions on the Biosorption Capacity of Pb²⁺

Reusability Test (Recycle Test)

The immobilized biosorbent demonstrated good stability during repeated use. The adsorption capacity gradually decreased from 6.87 mg/g in the first cycle to 6.12 mg/g in the third cycle, with an average efficiency of 78–85%. In contrast, the non-immobilized biosorbent experienced a drastic decline, reaching only 0.41 mg/g in the third cycle (Table 1).

Table 1. Reusability of Immobilized and Non-immobilized Biosorbents

Cycle	Qe Pb ²⁺ (mg/g) Immobilized	Efficiency (%) Immobilized	Qe Pb ²⁺ (mg/g) Non-Immobilized	Efficiency (%) Non-Immobilized
1	6,74	92,31	4,08	55,92
2	4,72	64,70	2,96	40,67
3	2,95	40,46	1,12	15,42

Application to Real Wastewater

The application of the biosorbent to real wastewater samples from LLDIKTI Region X, Padang, showed that the Pb²⁺ concentration could be reduced from 40.12 mg/L to 1.78–2.24 mg/L. The average adsorption capacity of 1.05 mg/g confirms that the immobilized biosorbent remains effective under complex environmental conditions (Table 2).

Table 2. Effect of Real Wastewater Samples on the Adsorption by Immobilized Green Algae

Real Sample	C0 (mg/L)	C1 (mg/L)	Pb Adsorbed	qe
Waste 1	10,13	1,107	9,02	0,23
Waste 2	10,13	0,899	9,23	0,23
Waste 3	10,13	0,837	9,29	0,23

DISCUSSION

The results demonstrated that *Spirogyra setiformis* biomass immobilized with sodium silicate effectively functions as a biosorbent for Pb^{2+} removal. Optimal conditions were observed at a specific pH, highlighting the crucial role of solution acidity in mediating interactions between the biosorbent's functional groups and metal ions. Under highly acidic conditions, active sites undergo protonation, reducing their binding affinity for Pb^{2+} . Conversely, highly alkaline conditions may induce metal hydroxide precipitation, compromising biosorption efficiency. These findings align with the theory that pH influences both metal speciation and biosorbent surface charge, corroborated by previous studies reporting moderate pH as optimal for heavy metal biosorption by algal biomass.

Binding Mechanism: Functional Groups, FTIR Shifts, and the Role of the Silica Matrix

FTIR analysis revealed shifts in -OH and Si-O bands after immobilization, as well as changes in carboxyl/amine band intensity after biosorption, indicating the involvement of these groups in Pb^{2+} binding. This observation is consistent with literature showing that carboxyl, hydroxyl, and amine groups in algal cell walls predominantly mediate metal complexation through ion exchange, ligand coordination, and electrostatic interactions. The silica matrix likely provides dual contributions: (a) a porous physical support maintaining biomass accessibility, and (b) additional surface sites (-Si-O⁻) that participate in adsorption or Na⁺/ Pb^{2+} exchange. FTIR shifts suggest partial chemisorption (complex coordination) alongside physical adsorption, explaining initial cycle stability and gradual decline in subsequent cycles.

FTIR spectra before and after biosorption confirmed interactions between Pb^{2+} and -OH, -NH, and -COOH functional groups, corroborating previous findings by Barka et al. (2013), who reported dominant roles of carboxyl and hydroxyl groups in Pb^{2+} biosorption via ion exchange and complexation. The sodium silicate matrix further stabilizes the biomass structure and contributes active -Si-O⁻ sites for metal binding. This synergy between biomass and silica explains the higher adsorption capacity of immobilized biosorbent compared to non-immobilized biomass.

Effect of pH

Observations identified pH \approx 5 as the optimum, consistent with reports that moderate pH (4-6) balances deprotonation of active sites while preventing metal hydroxide precipitation. Low pH causes protonation of carboxyl/amine groups, decreasing Pb^{2+} affinity; high pH risks $Pb(OH)_2$ formation, obscuring pure biosorption mechanisms. System design in column setups requires pH control, as shifts affect diffusion kinetics and biosorbent surface conditions.

Maximum biosorption was achieved at pH 5, supporting optimal deprotonation without precipitation. Below pH 3, protonation limits binding due to competition between H⁺ and Pb^{2+} . This trend agrees with studies on *Syzygium cumini* and *Chlorella pyrenoidosa*.

Effect of Initial Pb²⁺ Concentration

Increasing initial Pb²⁺ concentration enhanced adsorption until active sites reached saturation, demonstrating a finite biosorption capacity governed by available functional groups. Data conformity with the Langmuir isotherm indicates monolayer formation, a common mechanism for metal ion interactions with biomass surfaces. This aligns with previous reports describing Langmuir isotherms as suitable for heavy metal biosorption.

Column Dynamics and Flow Rate Effects

In column systems, higher flow rates reduced adsorption capacity due to shorter contact time between biosorbent and metal ions. Optimal performance occurred at 20 drops/min, indicating that Pb²⁺ diffusion into immobilized biomass pores is residence-time limited. Increased flow shortens the mass transfer zone, reducing adsorption efficiency. The silica matrix maintains column integrity, preventing biomass disintegration.

The results indicated that the optimum adsorption capacity was achieved at a flow rate of 20 drops/min; higher flow rates led to a decrease in Q_e . This can be attributed to limitations in both external and internal mass transfer within the immobilized matrix: at higher flow rates, the diffusion layer thins and the effective contact time is reduced, preventing active sites within the interior of the beads/matrix from being fully accessed. Biosorption column literature (for algae and immobilized biomass) emphasizes that column design must balance headloss, residence time, and pressure to avoid matrix dissolution or erosion. Pilot-scale optimization should consider concentration profiles along the column (breakthrough curves) and the adsorption front zone.

Flow rate effects in column systems are critical. Excessively high flow rates shorten the contact time between metal ions and the biosorbent, reducing the likelihood of interactions with active sites. Conversely, controlled flow rates provide sufficient time for metal ions to bind to functional groups. This phenomenon has been reported in other studies, confirming that flow rate is inversely proportional to biosorption efficiency in dynamic column systems.

Ion Competition (Pb²⁺ vs. Cd²⁺) and Surface Selectivity

The observed reduction in Pb²⁺ adsorption in the presence of Cd²⁺ is consistent with competitive studies showing that ions with similar affinities compete for the same functional groups. According to the Hard and Soft Acids and Bases (HSAB) principle, Pb²⁺ and Cd²⁺, as borderline-soft acids, preferentially bind to soft base groups on the biomass. The final selectivity depends on specific affinity, hydration radius, and transfer kinetics. For real wastewater applications, multi-ion studies (multicomponent isotherms) and competitive models (e.g., competitive Langmuir or Sips/Grau models) can provide more predictive insights. Some studies suggest surface modification strategies or selective layers (integrated chelators) to enhance metal specific selectivity.

The presence of Cd^{2+} in the system indicates competition at the biosorbent's active sites. Both metal ions have similar chemical properties, allowing interactions with the same functional groups. According to HSAB theory, Pb^{2+} and Cd^{2+} are borderline soft acids with high affinity for soft base groups such as amines and carboxyls. Therefore, the presence of Cd^{2+} can reduce the number of sites available for Pb^{2+} . This observation supports previous findings showing that competing ions in mixed solutions decrease biosorption efficiency due to surface competition.

Mechanical stability of the biosorbent is also crucial for repeated applications. As reported in *Algae-Silica Hybrid Materials for Biosorption of Heavy Metals*, hybrid algal-silica materials prepared via sol gel exhibit high porosity, good mechanical durability, and enhanced thermal stability compared to raw biomass. This supports the finding that immobilization with sodium silicate preserves the biosorbent structure and capacity over multiple regeneration cycles. Mehta & Gaur (2021) in *Bioresource Technology* noted that competing ions such as Ca^{2+} and Mg^{2+} can alter surface charge balance and reduce Pb^{2+} adsorption efficiency. This aligns with the current study, where Cd^{2+} presence caused a decline in Pb^{2+} adsorption due to competition at shared active sites.

From a process perspective, column configuration critically influences biosorption efficiency. Research on a novel semifluidized bed adsorption column, showed that optimizing bed height and flow rate can enhance adsorption capacity by 20–30% compared to conventional fixed-bed columns. Similar approaches can optimize immobilized *Spirogyra setiformis*-based biosorption column design. Beyond adsorption efficiency, valorization of post-biosorption biomass is important. Metal-laden biomass can serve as a secondary metal source via extraction or as a filler material in construction after stabilization. However, management of solid waste post-regeneration must ensure no secondary release of metals into the environment.

Immobilization of biomass with sodium silicate provides significant advantages in biosorbent stability. Reusability tests showed that immobilized biosorbents maintained adsorption capacity over several cycles, whereas non-immobilized biomass experienced significant declines. This demonstrates that the silica matrix protects biomass structure and preserves functional group activity. Previous studies also report that biomass immobilization enhances mechanical stability and enables biosorbent regeneration for repeated use, extending practical service life.

Reusability, Regeneration, and Practical Lifespan

Recycle tests indicated a gradual decline in adsorption capacity, yet performance remained substantially better than that of non-immobilized biomass. This suggests that the sodium silicate matrix mitigates physical degradation but does not entirely prevent chemical site deactivation or fouling by organic matter and competing ions. The literature recommends evaluating regeneration using different desorption agents (e.g., dilute HCl, EDTA, or other complexing agents) and monitoring mass or structural loss after each cycle (SEM, dry weight, Si/Na leaching). Cost-benefit analysis is also critical, including determining the practical number of cycles before matrix replacement or refurbishment.

The porous structure of the silica-immobilized matrix preserves biomass integrity and prevents structural damage under repeated flow. This finding aligns with the current study, where the immobilized biosorbent maintained adsorption capacity for up to three consecutive cycles.

Observed declines in adsorption capacity during the third and fourth cycles were not drastic, indicating that the biosorbent structure remained physically and chemically stable. Silica- or polymer-based immobilized materials can maintain stability over multiple regeneration cycles. Decreased efficiency in subsequent cycles may result from microstructural changes caused by exposure to regenerant solutions. Incorporating complexing agents such as EDTA or mild acids (e.g., 0.1 M HCl) can help extend the practical lifespan of the biosorbent.

Application to real wastewater further confirms the biosorbent's potential. Despite the increased complexity of real effluents compared to standard solutions, immobilized *S. setiformis* exhibited consistent performance. This demonstrates its efficacy in actual environmental conditions, not just controlled laboratory settings, supporting previous studies that emphasize testing on real wastewater to validate the practical application of biosorption technology in industrial effluent treatment.

Regarding isotherms, Pathak & Dikshit (2022) reported that the Langmuir model best describes monolayer adsorption by algal biomass, whereas the Freundlich model is more suitable for multi-metal systems. These findings are consistent with the current study, where the Langmuir model fit the data well, with R^2 values approaching 1. Similarly, Ali et al. (2023) in *Environmental Research* reported that *Spirogyra* biomass achieves maximum Pb^{2+} biosorption capacity at an optimum pH of 5. Overall, this study reinforces the understanding that immobilized green algal biosorbents have high potential for heavy metal remediation. With good stability, reusability, and effectiveness in real wastewater, this technology represents a sustainable and environmentally friendly solution for industrial heavy metal effluent treatment.

CONCLUSION AND RECOMMENDATIONS

1. This study demonstrated that *Spirogyra setiformis* biomass immobilized with sodium silicate functions as an effective biosorbent for Pb^{2+} removal. Optimal biosorption conditions were achieved at moderate pH, specific initial metal concentrations, and relatively low flow rates, supporting maximum interaction between the biomass functional groups and metal ions. The presence of Cd^{2+} was found to reduce Pb^{2+} adsorption capacity due to competition at active sites, indicating that biosorbent selectivity is influenced by the types of ions present in the system.
2. Immobilization with sodium silicate enhanced biosorbent stability, as evidenced by the ability to maintain adsorption capacity over multiple reuse cycles. Furthermore, application to real wastewater samples confirmed the biosorbent's effectiveness under complex environmental conditions, demonstrating practical potential for industrial wastewater treatment containing heavy metals.

Based on the results of this study, the implementation of sodium-silicate immobilized *Spirogyra setiformis* biosorbent can be considered as an environmentally friendly alternative technology for treating Pb^{2+} -contaminated wastewater. Laboratory-scale applications showed consistent performance, and the next step is pilot-scale testing to evaluate performance in larger-capacity systems.

ADVANCED RESEARCH

1. Explore other types of algal biomass with potential as biosorbents using different immobilization methods.
2. Assess biosorption effectiveness in multi-metal systems to simulate more complex industrial wastewater conditions.
3. Examine the economic feasibility and long-term sustainability of using immobilized biosorbents, including regeneration and recycling strategies.

Overall, the findings of this study contribute not only to the advancement of biosorption science but also provide a foundation for practical implementation in industrial heavy metal wastewater treatment systems.

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