RESEARCH ARTICLE

Application of *Staphylococcus aureus* for the Bioremediation of Lead (Pb) Contamination

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Abstract

Lampulo Marine Fishery Port in Banda Aceh is a major center for fishing and trade activities and is therefore vulnerable to heavy metal contamination. This study, conducted in December 2021, assessed lead (Pb) concentrations in sediment and water and evaluated the bioremediation potential of *Staphylococcus aureus*. Samples were collected using purposive sampling, and Pb levels were quantified by Inductively Coupled Plasma–Mass Spectrometry (ICP–MS). Initial concentrations ranged from 210.62–247.93 mg/kg in sediment and 161.91–168.23 mg/L in water, exceeding SEPA and Indonesian standards. Following treatment with *S. aureus*, Pb levels decreased to 0.72–2.72 mg/kg in sediment and 0.18–1.55 mg/L in water. These results demonstrate the strong biosorption capacity of *S. aureus* for marine lead bioremediation.

Keywords: Ocean Fishing Port, Lead, Inductively Coupled Plasma-Mass Spectrometry, Bioremediation.

1 Introduction

Heavy metal contamination in aquatic ecosystems poses a critical threat to environmental sustainability and human health. Among these contaminants, lead (Pb) is of particular concern due to its persistence, toxicity, and strong affinity for sediment accumulation. Common sources include deteriorating ship hull coatings, port activities, aquaculture operations, domestic wastewater discharge, oil spills, and industrial effluents [1]. Although natural background concentrations of heavy metals are typically low, intensified anthropogenic activities can substantially elevate Pb levels, resulting in long-term ecological degradation and contamination of aquatic food webs [2].

The Lampulo Oceanic Fishing Port (PPS Lampulo) in Banda Aceh represents a high-risk coastal zone characterized by concentrated maritime traffic and fish-processing activities. As one of the region's primary fish-landing centers, it is subject to continuous anthropogenic pressure [3]. Rapid coastal development, including aquaculture expansion, urban settlement growth, and industrial activities, further increases the vulnerability of surrounding waters to heavy metal accumulation [4]. Due to its bioaccumulative nature, chronic exposure to Pb through seafood consumption may cause hematological disorders, neurological impairment, gastrointestinal toxicity, and respiratory complications [5].

Although a previous assessment reported Pb concentrations below detectable limits (<0.0001 mg/L) in 2019 [4], no recent monitoring has evaluated whether increasing coastal pressure has altered contamination levels. Moreover, studies integrating

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updated contamination assessment with experimental bioremediation strategies remain limited in this region. Microbial bioremediation has emerged as a sustainable and cost-effective approach for heavy metal removal; however, the application of *Staphylococcus aureus* for Pb remediation in dynamic port environments has not been systematically evaluated [6].

Therefore, this study aims to (i) reassess current Pb concentrations in water and sediment at PPS Lampulo using ICP–MS and (ii) experimentally evaluate the biosorption potential of *Staphylococcus aureus* as a bioremediation agent. By integrating environmental monitoring with controlled remediation experiments, this research addresses a critical gap in localized heavy metal management strategies for intensively used coastal systems.

2 Methodology

2.1 General

The instruments and laboratory equipment used in this study included an Inductively Coupled Plasma–Mass Spectrometer (ICP–MS), microwave digestion system, analytical balance, drying oven, incubator, autoclave, laminar airflow cabinet, centrifuge, vacuum filtration apparatus, and pH meter. Additional materials included acid-cleaned glass vials (4 mL), volumetric flasks, Erlenmeyer flasks, beakers, volumetric pipettes, watch glasses, glass funnels, PVC sampling pipes, filter paper, RC/GHP syringe filters (0.20 µm), distilled water, nitric acid (HNO), and Lactose Broth (LB) medium. All reagents used were of analytical grade.

2.2 Study Area and Sampling

This study was conducted from December 2021 to February 2022 at the Lampulo Oceanic Fishing Port (PPS Lampulo), located in Kuta Alam District, Banda Aceh, Indonesia. The port is characterized by intensive maritime and commercial activities, including ship maintenance, docking, fuel handling, and fish-processing operations. Sampling stations were selected using purposive sampling based on anthropogenic risk factors, including hull maintenance areas and docking zones. Three stations, approximately 500 m apart, were established. Surface sediment and seawater samples were collected at each station, transferred into acid-cleaned glass vials, and transported to the laboratory in insulated containers with ice packs to preserve sample integrity. All laboratory analyses were performed at the Laboratory of Natural Sciences, National Institute of Education, Nanyang Technological University (NTU), Singapore.

2.3 Bacterial Strain and Culture Conditions

The bacterial strain used in this study was *Staphylococcus aureus*, obtained from the culture collection at Nanyang Technological University, Singapore, selected for its documented biosorption capacity toward heavy metals. The strain was cultured under sterile conditions at 37 °C in Lactose Broth (LB) medium for 24–48 h under aerobic conditions. Prior to application in bioremediation experiments, bacterial cultures were standardized to ensure consistent cell density and viability [9].

2.4 Lead (Pb) Analysis

Sediment and water samples were prepared using nitric acid (HNO) digestion. Samples were placed in acid-washed digestion vessels and dried at 105 °C where applicable. Each sample was treated with 10 mL of concentrated HNO and subjected to microwave-assisted digestion. The digested solutions were diluted with ultrapure water, homogenized, and filtered through 0.20 µm syringe filters prior to analysis [6]. Pb concentrations were quantified using ICP–MS following standard analytical protocols. Concentrations were calculated based on sample mass, dilution factor, and final volume. All measurements were conducted in triplicate to ensure analytical precision and reproducibility.

2.5 Bioremediation Experiment

Bioremediation experiments were conducted by inoculating sediment and seawater samples into LB medium supplemented with 1 mmol/L Pb. The bacterial inoculum was introduced under aseptic conditions, and samples were incubated at 37 °C for 48 h. Following incubation, Pb concentrations were re-measured using ICP–MS to evaluate removal efficiency. Pb reduction was calculated by comparing concentrations before and after treatment. All experiments were performed in triplicate, and statistical analyses were conducted to assess the significance of Pb removal.

3 Results

Lead (Pb) concentrations in sediment and water samples collected from the Lampulo Oceanic Fishing Port (PPS Lampulo) were quantified using Inductively Coupled Plasma–Mass Spectrometry (ICP–MS). The results revealed that Pb concentrations in sediment exceeded the threshold values established by the Swedish Environmental Protection Agency (SEPA), which classifies Pb levels between 100–400 mg/kg as indicative of high contamination. The detected concentrations therefore confirm substantial Pb accumulation in the sediments of the study area.

Similarly, Pb concentrations in seawater samples exceeded environmental quality standards outlined in Indonesian Government Regulation (PPRI) No. 22 of 2021 on Environmental Protection and Management. The regulation specifies maximum allowable Pb concentrations of 0.05 mg/L for port waters, 0.005 mg/L for marine tourism areas, and 0.008 mg/L for waters supporting marine biota. The measured values at PPS Lampulo were significantly higher than these limits, indicating serious contamination and potential ecological risk.

Bioremediation experiments were subsequently conducted using *Staphylococcus aureus*, a Gram-positive bacterium reported to possess Pb biosorption capability [Syari et al., 2018]. Morphological comparison of *S. aureus* colonies grown under control and Pb-exposed conditions revealed noticeable differences, including darker pigmentation and altered colony morphology in Pb-supplemented media, suggesting stress response and potential lead accumulation (Figure 1). Application of *S. aureus* resulted in substantial reductions in Pb concentrations in both sediment and water samples. Post-treatment measurements demonstrated marked decreases in Pb levels, indicating effective biosorption and stabilization of lead. In water samples, Pb concentrations were reduced toward regulatory thresholds, highlighting the potential of *S. aureus* as a bioremediation agent in heavily impacted coastal environments such as PPS Lampulo.

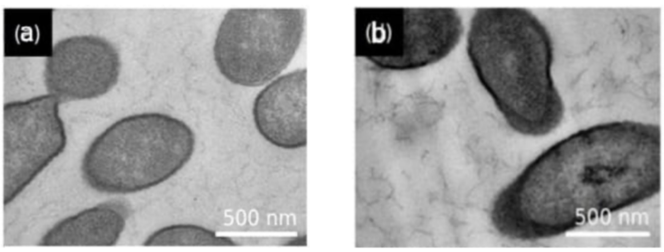

Figure 1. Figure 1. Morphological comparison of *Staphylococcus aureus* colonies: (a) control on LB medium without Pb; (b) LB medium supplemented with 1 mmol/L Pb, showing pigmentation and morphological changes under lead exposure.

4 Discussion

The elevated concentrations of lead (Pb) detected in sediment samples from the Lampulo Oceanic Fishing Port (PPS Lampulo) reflect substantial anthropogenic pressure on the surrounding marine environment. Measured sediment Pb levels ranged from 210.62 to 247.93 mg/kg, placing the study area within the "high contamination" category according to Swedish Environmental Protection Agency (SEPA) guidelines. Lead exhibits a strong affinity for particulate matter and organic detritus, facilitating its accumulation and long-term persistence in sediments. Once deposited, Pb can bind to clay minerals, iron–manganese oxides, and organic matter, reducing immediate mobility but creating a long-term reservoir of contamination. The observed contamination is likely associated with cumulative inputs from port-related activities, including vessel maintenance, fuel handling, hull paint degradation, and waste discharge, all of which contribute to localized metal enrichment in coastal sediments [7].

Bioremediation using *Staphylococcus aureus* resulted in a pronounced decline in sediment Pb concentrations to 0.72–2.72 mg/kg, representing a substantial removal efficiency under controlled laboratory conditions. In parallel, seawater samples initially exhibited Pb concentrations between 161.91 and 168.23 mg/L, far exceeding the Indonesian regulatory threshold of 0.05 mg/L for port waters. Following treatment, concentrations decreased significantly to 0.18–1.55 mg/L. The comparative reduction in Pb concentrations across sediment and water samples at the three sampling stations is illustrated in (Figure 2), demonstrating consistent removal trends.

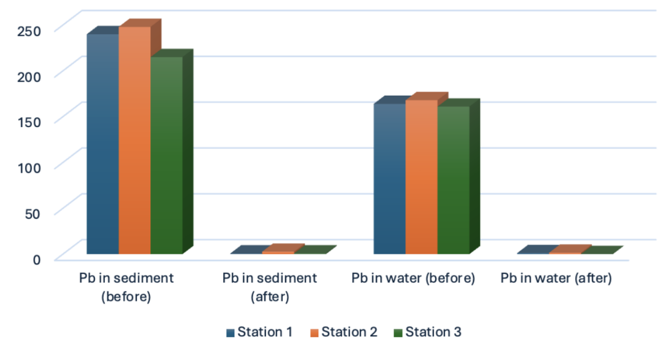

Figure 2. Comparison of Pb concentrations in sediment and seawater at three PPS Lampulo stations before and after bioremediation.

The marked decline in Pb levels highlights the biosorption capacity of *S. aureus*, which is mediated by functional groups within the bacterial cell wall, including carboxyl, phosphate, hydroxyl, and amine moieties. These groups facilitate ion exchange, surface complexation, and intracellular sequestration processes. In addition to passive adsorption, active metabolic pathways may contribute to metal immobilization or transformation into less bioavailable forms. The darker pigmentation observed in Pb-exposed colonies further supports the occurrence of stress-induced metal accumulation [8].

Despite achieving reductions exceeding 99% in several samples, some post-treatment concentrations remained above environmental standards, indicating that laboratory-scale effectiveness may not directly translate to complete compliance under natural conditions [9]. Environmental variables such as salinity, competing ions, temperature fluctuations, and hydrodynamic forces could influence biosorption efficiency in situ. Therefore, while the findings confirm the strong potential of *S. aureus* as a bioremediation agent [10], further studies focusing on kinetic modeling, adsorption isotherms, long-term stability, and pilot-scale applications are required to evaluate practical implementation in dynamic coastal ecosystems.

5 Conclusion

This study confirms that lead (Pb) concentrations in sediment and water from the Lampulo Oceanic Fishing Port (PPS Lampulo) exceed established national and international environmental quality standards, reflecting significant anthropogenic contamination. The elevated Pb levels indicate sustained inputs associated with port-related activities and coastal development. Bioremediation experiments using *Staphylococcus aureus* resulted in substantial reductions in Pb concentrations in both sediment and water under controlled laboratory conditions. The marked decrease in Pb levels demonstrates the bacterium's biosorption and immobilization capacity, highlighting its potential as a biological agent for mitigating heavy metal pollution in marine environments. Although the results are promising, further in situ studies are required to evaluate long-term stability, environmental interactions, and scalability before practical implementation in dynamic coastal ecosystems can be recommended.

Data Availability Statement

Data will be made available on request.

Author Contributions

A.K.S. and S.K. contributed to the conceptual design of the study. A.K.S. carried out the methodology development, formal analysis, investigation, data curation, visualization, and preparation of the original manuscript draft. Validation of the results was conducted jointly by A.K.S. and S.K. All authors have read and approved the final manuscript for publication.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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