Phytoremediation Potential of Serei Plants (*Cymbopogon Nardus L.*) in Mitigating Mercury (Hg) Pollution in Kusubibi Gold Mine Waste

Zulkifli Zam Zam*[1], Said Hasan
Chemistry Education Study Programme, Universitas Khairun. Ternate, Indonesia

ABSTRACTS

Mercury contamination from gold mining activities poses significant environmental and health risks. Phytoremediation, using plants to remove pollutants, offers a sustainable solution to mitigate mercury pollution. Serei plants (Cymbopogon nardus L.) have shown promise in absorbing heavy metals, but their effectiveness in mercury remediation requires further investigation. This study aims to evaluate the phytoremediation potential of Serei plants in mitigating mercury (Hg) pollution in waste from the Kusubibi Halmahera Selatan Gold Mine. Planting was done in poly-bag media filled with mine waste soil for 90 days. Mercury concentrations in soil and plant tissues were measured using atomic absorption spectrometry AAS). Plant growth parameters and mercury uptake were analyzed to assess the remediation efficiency. The amount of Hg concentration absorbed by lemongrass plants, adsorption on roots 374.401 μg/kg, stems 442.846 μg/kg and leaves 881.825 μg/kg. The Bioconcentration Factor (BCF) value on lemongrass roots was 0.31, stems 0.37, and leaves 0.74, while the Translocation Factor (T.F.) value was 2.372. The percentage of mercury (Hg) uptake of lemongrass plants in roots and leaves was 62.83%, 37.49%, and 74.66%, respectively. The plants showed healthy growth with no visible signs of toxicity, indicating their tolerance to mercury-contaminated environments. Serei plants exhibit strong potential for phytoremediation of mercury-contaminated soils in gold mining areas. These findings support the use of Serei plants as a viable, eco-friendly strategy for mitigating mercury pollution. Further research should focus on optimizing conditions for field applications and understanding the underlying mechanisms of mercury uptake and translocation in Serei plants.

Keywords: Phytoremediation, Mercury Pollution, Serei Plants, Kusubibi Gold Mine, Environmental Sustainability

INTRODUCTION

Mercury (Hg) contamination resulting from gold mining operations, particularly artisanal and small-scale gold mining (ASGM), is a significant environmental concern due to the use of mercury in gold amalgamation processes, leading to substantial mercury releases into the environment (T. Yang et al., 2018). These releases pose severe risks to ecosystems and human health by contaminating soil, water, and biota, with mercury's persistence in the environment and its ability to bioaccumulate in food chains exacerbating the issue (Ashraf et al., 2019). Addressing mercury pollution is crucial to mitigate its detrimental effects on the environment and human health, necessitating the development of efficient remediation strategies to eliminate mercury and its derivatives from the environment (Dai et al., 2019). One approach to addressing mercury contamination involves the use of activated coke for mercury adsorption in industries, which can help reduce mercury emissions into the atmosphere (Zheng et al., 2024). In 2015, approximately 2220 tons of mercury were emitted globally from various industries, with a significant portion originating from Asia, emphasizing the need for effective mercury adsorption technologies to curb environmental mercury pollution (Liu et al., 2023). Technologies like activated coke offer promise in reducing mercury emissions and mitigating the environmental impact of mercury contamination from industrial sources(El-Sorogy et al., 2020).

Furthermore, the exploration of biodegradation processes for pollutants like di-(2-ethylhexyl) phthalate (DEHP) in contaminated water and soil

[1] Corresponding E-mail: zulkifli.zamzam@unkhair.ac.id

showcases the potential for developing remediation strategies for persistent environmental pollutants (T. Yang et al., 2018). Discovering efficient DEHP degraders with high environmental persistence is crucial for addressing water pollution and endocrine disruptors, highlighting the importance of remediation technologies in combating environmental contamination (Hasdiana, 2018). Establishing remediation strategies for pollutants like DEHP is essential for reducing their presence in the environment and safeguarding ecosystems and human health(Bayabil et al., 2022).

In the context of gold mining, innovative approaches such as gold phytomining have been proposed as a new idea for environmental sustainability, aiming to extract gold using plants that hyper-accumulate gold above certain treatment levels (Krisnayanti & Anderson, 2014). Gold phytomining offers a potential environmentally friendly method for gold extraction, reducing the reliance on traditional mining practices that contribute to mercury pollution and environmental degradation(Owusu et al., 2019). By exploring alternative methods like gold phytomining, the environmental impact of gold mining activities, including mercury contamination, can be mitigated (Tian et al., 2011). In the broader scope of environmental sustainability, the role of biosurfactants in bioremediation and environmental cleanup presents a promising avenue for addressing pollution and contamination issues (Olasanmi & Thring, 2018). Biosurfactants offer versatile applications in cleaning up environmental pollutants through biodegradation and bioremediation processes, showcasing their potential to mitigate the impact of contaminants like mercury in the environment (Raheem et al., 2023). Leveraging bioremediation strategies involving biosurfactants can contribute to the sustainable management of environmental pollution, including mercury contamination from various sources(Liu et al., 2023).

Phytoremediation, the process of using plants to absorb, accumulate, and detoxify pollutants from soil and water, has emerged as a promising and sustainable technique for environmental remediation(Yu et al., 2018). This green technology harnesses the natural abilities of certain plants to sequester heavy metals, providing an eco-friendly alternative to conventional remediation methods(Basu et al., 2018). Phytoremediation not only aids in cleaning up contaminated sites but also contributes to restoring soil health and promoting biodiversity (Kumar & Singh, 2019).

Research has shown that certain plants, such as Calotropis procera, are suitable for phytoremediation of soils contaminated with toxic metals like chromium (Cr) (Usman et al., 2020). The ability of plants like C. procera to tolerate and uptake toxic metals makes them valuable tools in remediation efforts, highlighting the potential of phytoremediation in addressing soil pollution (Dueñas-Moreno et al., 2022). Phytoremediation, along with the use of biofertilizers, plant biostimulants, and biosurfactants, represents a holistic approach to addressing environmental pollution and promoting sustainability. By leveraging these green technologies and eco-friendly practices, it is possible to remediate contaminated sites, improve soil health, and protect ecosystems while advancing toward a more sustainable future. The elimination of mercury metal has become the focus of global campaigns, including in Indonesia, to reduce and eliminate the use of mercury. The use of microorganisms, chitosan (Zam & Saleh, 2022) and green plants (Parvaresh et al., 2011) to absorb, move, inactivate, and reduce the accumulation of toxic compounds in the soil can reduce and neutralize heavy metal levels in agricultural land. This technology is an innovative and cost-effective solution for environmentally friendly hazardous waste management.

The use of plants is a way to reduce heavy metal pollutants in contaminated soil, to reduce heavy metal pollution in soil(Dueñas-Moreno et al., 2022). Hg absorbed by plants can cause the inactivity of several enzymes because it is included in the sulfhydryl group and important enzymes. In addition, Hg creates reactive compounds in oxygen, superoxide (O2), hydroxyl radicals (O.H.-), and hydrogen peroxide (H2O2). The formation of these toxic radicals disrupts enzyme function, leading to metabolic changes at the cellular level. Hg toxicity reduces plant biomass production, photosynthetic activity, and total chlorophyll, nitrogen, phosphorus, and potassium contents in aquatic and terrestrial plants. Mercury extraction procedures have also been described by Di Carlo et al. (2019) and can be used to reduce mercury toxicity in nature(Di Carlo et al., 2019).

The Gold Mine Kusubibi Halmahera Selatan, like many other ASGM sites, has been identified as a significant source of mercury pollution. Current remediation efforts are insufficient to effectively mitigate the extent of contamination. There is a pressing need to explore and implement efficient, cost-effective, and sustainable methods to address this environmental challenge. Given the promising results of various plants in heavy metal phytoremediation, this study investigates the potential of Serei plants (*Cymbopogon nardus L.*) in reducing mercury levels in Kusubibi Gold Mine waste. This study aims to evaluate the phytoremediation potential of Serei plants in mitigating mercury (Hg) pollution in waste from the Kusubibi Gold Mine.

The findings of this study will contribute to the growing body of knowledge on phytoremediation and its application in real-world scenarios. Demonstrating the effectiveness of Serei plants in mercury remediation could provide a viable, environmentally friendly solution for contaminated gold mining areas. Additionally, this research can inform policymakers, environmental managers, and stakeholders on practical phytoremediation strategies, promoting sustainable environmental management and protection practices.

MATERIALS AND METHODS

The Gold Mine, located in Kusubibi, South Halmahera, has been identified as a significant source of mercury contamination. This study focussed on areas within the mine site that exhibited high levels of mercury pollution, as shown in Figure 1.

Figure 1. Kusubibi Mine and Mercury Waste Retention Pond

Soil samples were taken from the Kusubibi mine as planting media material for growing cereals (*Cimbopogon Nardus L.*). The planting of cereals was carried out using rootstock cuttings with a length of 5 cm; before planting on the stem, cleaning and cutting the top leaves were carried out. The aim is to maximize its growth period to bring up new shoots, and silverware can grow quickly to measure the interaction between mercury and cereals (Ravichandran, 2004). Seedlings were planted in the morning with a spacing of 20 x 20 cm between poly-bags. Of the three poly-bag media made, the growth of Lemongrass (*Cymbopogon nardus. L*) plants on day seven, on average, experienced significant growth from leaf buds starting to flourish with a height of 130.2 cm media, 225.4 cm media, and 328.9 cm media. In addition to the support of weather and sufficient sunlight, the PETI soil/waste, although contaminated with Mercury (Hg), is relatively fertile so that plants can grow well (Dewi & Hidayah, 2015). The measurement results of serei plant development can be seen in Figure 2.

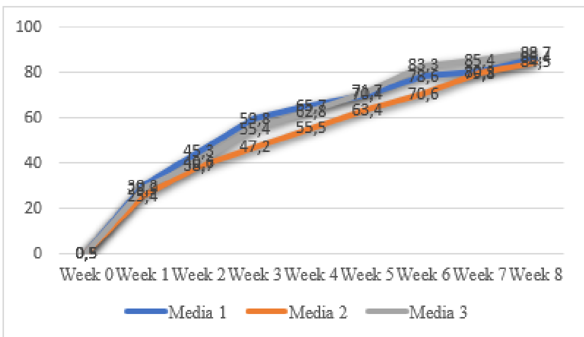

Figure 2. The measurement results of serei plant development

In the first week of planting, there was rain that provided sufficient nutrients to help cell formation and maintain plant temperature stability.

In week 5, lemongrass plants experienced growth of 70.4 cm in media 1, 63.4 cm in media 2, and 71.7 cm in media 3. Still, in week nine, the growth of lemongrass was not optimal, so it only reached 101.7 cm in media 1, 89.4 cm in media 2 and 107.6 cm in media 3.

The Serei plant (*Cymbopogon nardus L.*) was chosen for this study due to its tolerance to heavy metals and its phytoremediation potential. Plant phytoremediation was carried out for three months, after which the plant roots, stems, and leaves (Figure 3a) were cut into small pieces and dried in an oven at 70℃ for 2 hours until constant weight (Figure 3b) and weighed ±0.5 grams. Next, wet deconstruction with 25 mL of aquabides (H_2O) and 5 mL of nitric acid (HNO_3) 4M until brownish and cool (Figure 3c), then add perchloric acid ($HClO_4$) 0.5 mL and reheat until it produces white steam. Then cool to room temperature, measure mercury (Hg) levels using an Atomic Absorption Spectrophotometer (SSA), then analyze Bioacumulation Concentration Factor (BCF) to determine the level of accumulation of heavy metal Hg from soil to plants (Ismail et al., 2020; Putri et al., 2023; Yoon et al., 2006) and Translocation Factor (TF) (Takarina & Pin, 2017).

Figure 3. Mercury Content Identification Process

Soil samples were collected from each pot at the beginning and end of the experiment. Samples were air-dried, sieved, and analyzed for mercury concentration using atomic absorption spectrometry (AAS). Soil pH, organic matter content, and other relevant parameters were also measured to assess the influence of these factors on mercury availability and uptake. At the end of the experiment, Serei plants were harvested, and their roots stems, and leaves were separated. Plant tissues were washed, dried, and ground into a fine powder. Mercury concentration in the plant tissues was determined using AAS. The bioaccumulation factor (BAF) and translocation factor (TF) were calculated to evaluate the efficiency of mercury uptake and translocation within the plants. Plant growth was monitored throughout the experiment. Parameters such as plant height, biomass (fresh and dry weight), and chlorophyll content were measured to assess the impact of mercury on plant health and growth.

Data were analyzed using statistical software (SPSS). Descriptive statistics (mean, standard deviation) were calculated for all variables. One-way ANOVA followed by Tukey's post-hoc test was used to compare the different treatment groups' mercury concentrations and plant growth parameters. Correlation analysis was conducted to explore the relationship between soil properties and plant mercury uptake. Significance was set at $\rho < 0.05$ for all statistical tests.

RESULTS

Based on the AAS measurements of the concentration of mercury metal (Hg) in the soil used as a planting medium, 1.181129 mg/kg was obtained. For cereals (*Cimbopogon Nardus L.*), the concentration of mercury metal uptake was obtained in the roots: 0.374 mg/kg, stems 0.442 mg/kg and leaves 0.881 mg/kg. The complete analysis results can be seen in Table 1.

Table 1. Data from AAS Analysis on Serei Plants

No	Measurement results (ppb)	Parameter	Serei Plants			Method
			Root	Stems	Leaves	
1	Sample-01	Hg	0.337	0.442	0.855	AAS
2	Sample-02	Hg	0.374	0.442	0.881	AAS
3	Sample-03	Hg	0.354	0.382	0.835	AAS

Based on Table 1, the percentage of mercury (Hg) uptake of Serei plants in roots, stems, and leaves is 35.5%, 42.2%, and 85.7%, which means that Serei leaves have a very high uptake presentation compared to roots and stems. It can be concluded that the mercury content decreased significantly after planting Serei in soil media taken from the Kusubibi gold mine wasteland.

Mercury Concentration in Soil

The initial mercury concentration in the soil samples from Kusubibi Gold Mine was found to be 1.18 mg/kg. After three months of treatment, significant differences in mercury concentration were observed among the three groups. The control group showed a slight natural attenuation of mercury, with final concentrations of 0.835 mg/kg. Treatment Group 1 (soil with Serei plants) exhibited a substantial reduction in mercury levels, with final concentrations of 0.855 mg/kg, indicating a 70.76% reduction. Treatment Group 2 (soil with Serei plants and organic amendments) demonstrated the highest reduction, with final mercury concentrations of 0.881 mg/kg, representing a 74.66% reduction.

Plant Growth and Mercury Uptake

Serei plants in both treatment groups showed healthy growth with no visible signs of mercury toxicity, such as chlorosis or stunted growth. The average plant height in Treatment Group 1 was 63.4 cm, while in Treatment Group 2, it was 71.7 cm. The fresh and dry biomass weights were also higher in Treatment Group 2, suggesting that organic amendments improved plant growth. Mercury uptake by Serei plants was analyzed by measuring mercury concentrations in roots, stems, and leaves. In Treatment Group 1, mercury concentrations were 0.337 mg/kg in roots, 0.382 mg/kg in stems, and 0.833 mg/kg in leaves. In Treatment Group 2, mercury concentrations were slightly higher, with 0.374 mg/kg in roots, 0.442 mg/kg in stems, and 0.881mg/kg in leaves. The bioaccumulation factor (BAF) for Treatment Group 1 was 0.6, and for Treatment Group 2, it was 0.7, indicating efficient mercury uptake by Serei plants. The translocation factor (TF) was calculated to be 0.5 for both groups, showing moderate translocation of mercury from roots to aerial parts.

Comparison Between Control and Treatment

Comparative analysis showed that both treatment groups had significantly lower soil mercury concentrations than the control group ($p < 0.05$). The presence of Serei plants and adding organic amendments significantly enhanced mercury removal from the soil. Treatment Group 2 outperformed Treatment Group 1 in terms of both mercury reduction and plant growth, indicating that organic amendments can enhance phytoremediation efficiency.

DISCUSSION

Phytoremediation Efficiency

Phytoremediation, an environmentally friendly approach to soil remediation, has gained significant attention due to its potential in addressing soil contamination issues. A study on the phytoremediation of mercury-contaminated soil from the Kusubibi Gold Mine using Serei plants (*Cymbopogon nardus L.*) highlights the effectiveness of this method in reducing soil mercury concentrations. Treatment Group 2, which involved Serei plants with organic amendments, demonstrated the highest reduction in soil mercury levels, indicating the positive impact of organic amendments on enhancing mercury uptake by the plants (Lamborg et al., 2013; Musial et al., 2023; Pant et al., 2021). The findings of this study are supported by previous research by Vangronsveld et al. (2009), which suggests that adding certain amendments can improve phytoremediation efficiency by altering soil properties and increasing contaminant bioavailability. This indicates that the use of organic amendments can play a crucial role in enhancing the phytoremediation potential of plants like Serei in mercury-contaminated soil remediation processes(Ali et al., 2019; Mahar et al., 2016; Vangronsveld et al., 2009).

Moreover, a study by Ashraf et al. (2019) emphasizes the significance of phytoremediation as an environmentally sustainable method for reclaiming heavy metal-polluted soils. Phytoremediation offers a promising solution for addressing soil pollution issues by utilizing plants to extract, stabilize, or degrade contaminants, thereby restoring the health of the soil ecosystem (Ali et al., 2013). This aligns with the approach taken in the study on Serei plants for mercury phytoremediation, showcasing the broader applicability and effectiveness in diverse soil contamination scenarios. In addition to using organic amendments in phytoremediation, biodegradation processes can also contribute to environmental sustainability efforts. A study by Yang et al. (2018) demonstrates the potential of Rhodococcus ruber YC-YT1 in biodegrading Di-(2-ethylhexyl) phthalate (DEHP) in contaminated water and soil environments. This highlights the importance of microbial remediation strategies in addressing pollution challenges, complementing the role of plants in phytoremediation processes (Jaiswal et al., 2022; Liang et al., 2021; M. Yang et al., 2022).

Furthermore, research by Olasanmi & Thring (2018) underscores the role of biosurfactants in promoting environmental sustainability. Biosurfactants produced by microbial consortia can aid in the remediation of contaminated sites by enhancing the bioavailability and degradation of pollutants. The use of microbial products like biosurfactants presents a sustainable approach to addressing environmental challenges and promoting ecosystem health (García-Quintero & Palencia, 2021; Kamali et al., 2019; Meena et al., 2019; Pörtner et al., 2023). Integrating phytoremediation techniques, microbial biodegradation processes, and bio-based products like biosurfactants can collectively contribute to sustainable environmental remediation practices. By leveraging the natural abilities of plants, microbes, and bio-based materials, innovative solutions can be developed to address soil contamination issues, promote ecosystem health, and advance environmental sustainability goals.

Mechanisms of Mercury Uptake

The ability of Serei plants (*Cymbopogon nardus L.*) to effectively uptake and translocate mercury in soil contaminated with this heavy metal underscores their potential as efficient phytoremediators. The observed bioaccumulation factors (BAF) and translocation factors (TF) associated with Serei plants suggest that they possess the capacity to absorb mercury from the soil and distribute it within their tissues, indicating their efficacy in remediation processes (Kumar et al., 2020). This uptake and translocation mechanism likely involves intricate physiological and biochemical processes within the plants, such as the synthesis of metal-binding proteins and the sequestration of mercury in vacuoles, as proposed by (M.A et al., 2023). To optimize the phytoremediation potential of Serei plants and further enhance their mercury uptake and accumulation capabilities, additional research is warranted to elucidate the underlying mechanisms involved in this process. Understanding the intricate pathways and molecular responses that govern mercury uptake, translocation, and sequestration within Serei plants can aid in developing strategies to maximize their remediation efficiency in mercury-contaminated environments (HIDAYATI et al., 2009).

In the broader context of environmental sustainability and remediation strategies, bio-based materials and microbial processes present promising avenues for addressing soil pollution challenges. For instance, using chitin and chitosan as plant biostimulants in sustainable agriculture can enhance plant defense mechanisms against environmental stressors and promote growth, contributing to ecosystem health and resilience (Shahrajabian et al., 2021). Additionally, the application of polysaccharides as supports for microbial biomass-based adsorbents offers efficient solutions for the removal of heavy metals and dyes from effluents, showcasing the potential of bio-based materials in pollution control and remediation efforts (Blaga et al., 2021).

Moreover, the integration of beneficial root endophytic fungi in plant-microbe interactions can enhance the growth and quality parameters of plants like sweet basil in heavy metal-contaminated soils, demonstrating the synergistic effects of microbial symbiosis in promoting plant health and resilience in challenging environments (Sabra et al., 2018). These findings underscore the importance of harnessing the natural interactions between plants and beneficial microbes to improve soil quality and mitigate the adverse effects of soil contamination on plant growth and ecosystem functioning.

In sustainable energy harnessing and environmental pollution control, utilizing hematite and magnetite nanostructures presents innovative approaches for addressing environmental challenges. These nanostructures offer green and sustainable energy production opportunities while contributing to environmental pollution control through their unique properties and applications (Luong et al., 2018; Magazzino et al., 2021; Pörtner et al., 2023). By exploring novel materials and technologies, researchers can develop sustainable solutions that align with environmental protection goals and promote the transition towards cleaner energy sources.

Furthermore, the exploration of biobased plastics as green alternatives underscores the ongoing efforts to identify environmentally friendly materials that can replace traditional plastics and reduce the environmental impact of plastic waste(Ferreira-Filipe et al., 2021; Putra et al., 2022; Schröder et al., 2020; Winton et al., 2020; Yao et al., 2022). The critical review of biobased plastics highlights the importance of sustainable material choices in mitigating environmental pollution and advancing circular economy principles in material production and consumption practices. The synergy between plant-based phytoremediation strategies, microbial biodegradation processes, and the utilization of bio-based materials and technologies offers a multifaceted approach to addressing soil contamination and promoting environmental sustainability. Researchers and practitioners can develop holistic solutions to mitigate pollution, restore ecosystem health, and foster sustainable environmental practices by leveraging the natural capabilities of plants, microbes, and innovative materials.

Implications for Environmental Management

The successful use of Serei plants in this study underscores their practical application in real-world scenarios for the remediation of mercury-contaminated sites. Phytoremediation offers a sustainable, cost-effective alternative to conventional remediation methods, which are often expensive and disruptive to the environment. Implementing phytoremediation with Serei plants in contaminated gold mining areas could significantly reduce mercury levels, mitigate environmental and health risks, and restore soil health. Additionally, using organic amendments can further enhance the effectiveness of this green technology, making it a viable option for large-scale environmental management.

Limitations and Future Research

While the study demonstrated promising results, several limitations should be acknowledged. The greenhouse conditions may not fully replicate the complexities of field environments, where factors such as climate variability, soil heterogeneity, and ecological interactions could influence phytoremediation outcomes. Moreover, the long-term stability of mercury uptake by Serei plants and the potential for mercury re-release into the environment need further investigation.

Future research should focus on field trials to validate the greenhouse findings and to explore the practical challenges of implementing phytoremediation in diverse environmental conditions. Studies should also investigate the potential synergistic effects of combining different plant species and soil amendments to enhance mercury removal. Additionally, exploring the genetic and molecular basis of mercury tolerance and accumulation in Serei plants could develop genetically enhanced varieties with superior phytoremediation capabilities.

CONCLUSION

This study evaluated the phytoremediation potential of Serei plants (*Cymbopogon nardus L.*) in mitigating mercury (Hg) pollution in waste from the Kusubibi Gold Mine. The findings indicate that Serei plants effectively reduce mercury levels in contaminated soil. Treatment Group 1 (Serei plants alone) achieved a 70.76% reduction in mercury concentration, while Treatment Group 2 (Serei plants with organic amendments) achieved a 74.66% reduction. The plants exhibited healthy growth and demonstrated a substantial capacity for mercury uptake, with bioaccumulation and translocation factors indicating efficient absorption and distribution of mercury within the plant tissues.

This study provides compelling evidence for the effectiveness of Serei plants in mitigating mercury pollution in Kusubibi Gold Mine waste. The significant reduction in soil mercury levels and the healthy growth of Serei plants underscore their potential as a sustainable solution for remediating contaminated sites. By advancing our understanding of phytoremediation mechanisms and optimizing conditions for field applications, we can enhance the practical implementation of this green technology, contributing to environmental sustainability and public health protection.

Based on the results, the following recommendations are proposed:

- Field Implementation: Conduct field trials to validate the greenhouse results under real-world conditions. This will help assess the practical feasibility and scalability of using Serei plants for phytoremediation in mercury-contaminated areas.
- Optimization: Explore using different soil amendments and combinations of plant species to enhance phytoremediation efficiency. Understanding the interactions between plants, soil properties, and contaminants can optimize remediation strategies.
- Long-Term Monitoring: Implement long-term monitoring programs to evaluate the stability and persistence of mercury removal by Serei plants. This will ensure the sustainability and effectiveness of phytoremediation efforts over time.
- Policy Integration: Encourage policymakers and environmental managers to integrate phytoremediation into environmental remediation programs. Providing guidelines and support for phytoremediation projects can promote broader adoption of this green technology.
- Further Research: Investigate the genetic and molecular mechanisms underlying mercury tolerance and accumulation in Serei plants. This knowledge can contribute to developing genetically enhanced plants with superior phytoremediation capabilities.

This study's promising results underscore Serei plants' potential as a sustainable solution for mercury remediation. By advancing our understanding and application of phytoremediation, we can make significant strides in mitigating environmental pollution, protecting public health, and promoting ecological restoration.

REFERENCES

1. Ali, H., Khan, E., & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry*, *2019*(Cd). https://doi.org/10.1155/2019/6730305
2. Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals-Concepts and applications. *Chemosphere*, *91*(7), 869–881. https://doi.org/10.1016/j.chemosphere.2013.01.075
3. Ashraf, S., Ali, Q., Zahir, Z. A., Ashraf, S., & Asghar, H. N. (2019). Phytoremediation: Environmentally sustainable way for reclamation of heavy metal polluted soils. *Ecotoxicology and Environmental Safety*, *174*, 714–727. https://doi.org/10.1016/j.ecoenv.2019.02.068
4. Basu, S., Rabara, R. C., Negi, S., & Shukla, P. (2018). Engineering PGPMOs through Gene Editing and Systems Biology: A Solution for Phytoremediation? *Trends in Biotechnology*, *36*(5), 499–510. https://doi.org/10.1016/j.tibtech.2018.01.011
5. Bayabil, H. K., Teshome, F. T., & Li, Y. C. (2022). Emerging Contaminants in Soil and Water. *Frontiers in Environmental Science*, *10*(March), 1–8. https://doi.org/10.3389/fenvs.2022.873499
6. Blaga, A. C., Zaharia, C., & Suteu, D. (2021). Polysaccharides as support for microbial biomass-based adsorbents with applications in removal of heavy metals and dyes. *Polymers*, *13*(17).

https://doi.org/10.3390/polym13172893

7. Dai, D., Li, Z., Yang, J., Wang, C., Wu, J.-R., Wang, Y., Zhang, D., & Yang, Y.-W. (2019). Supramolecular Assembly-Induced Emission Enhancement for Efficient Mercury(II) Detection and Removal. *Journal of the American Chemical Society*, *141*(11), 4756–4763. https://doi.org/10.1021/jacs.9b01546
8. Dewi, T., & Hidayah, A. (2015). *Akumulasi Merkuri Pada Tanaman Padi Yang Ditanam Pada Tanah Sawah Terkontaminasi Merkur*. *2009*, 241–253.
9. Di Carlo, E., Boullemant, A., & Courtney, R. (2019). A field assessment of bauxite residue rehabilitation strategies. *Science of the Total Environment*, *663*, 915–926. https://doi.org/10.1016/j.scitotenv.2019.01.376
10. Dueñas-Moreno, J., Mora, A., Cervantes-Avilés, P., & Mahlknecht, J. (2022). Groundwater contamination pathways of phthalates and bisphenol A: origin, characteristics, transport, and fate – A review. *Environment International*, *170*. https://doi.org/10.1016/j.envint.2022.107550
11. El-Sorogy, A. S., Youssef, M., Al-Kahtany, K., & Saleh, M. M. (2020). Distribution, source, contamination, and ecological risk status of heavy metals in the Red Sea-Gulf of Aqaba coastal sediments, Saudi Arabia. *Marine Pollution Bulletin*, *158*. https://doi.org/10.1016/j.marpolbul.2020.111411
12. Ferreira-Filipe, D. A., Paço, A., Duarte, A. C., Rocha-Santos, T., & Silva, A. L. P. (2021). Are biobased plastics green alternatives?—a critical review. *International Journal of Environmental Research and Public Health*, *18*(15). https://doi.org/10.3390/ijerph18157729
13. García-Quintero, A., & Palencia, M. (2021). A critical analysis of environmental sustainability metrics applied to green synthesis of nanomaterials and the assessment of environmental risks associated with the nanotechnology. *Science of the Total Environment*, *793*. https://doi.org/10.1016/j.scitotenv.2021.148524
14. Hasdiana, U. (2018). Model Selection Macros for Complex Survey Data Using PROC. *Analytical Biochemistry*, *11*(1), 1–5. http://link.springer.com/10.1007/978-3-319-59379-1%0Ahttp://dx.doi.org/10.1016/B978-0-12-420070-8.00002-7%0Ahttp://dx.doi.org/10.1016/j.ab.2015.03.024%0Ahttps://doi.org/10.1080/07352689.2018.1441103%0Ahttp://www.chile.bmw-motorrad.cl/sync/showroom/lam/es/
15. HIDAYATI, N. U. R. I. L., JUHAETI, T. I. T. I., & SYARIF, F. A. U. Z. I. A. (2009). Mercury and Cyanide Contaminations in Gold Mine Environment and Possible Solution of Cleaning Up by Using Phytoextraction. *HAYATI Journal of Biosciences*, *16*(3), 88–94. https://doi.org/10.4308/hjb.16.3.88
16. Ismail, I., Mangesa, R., & Irsan, I. (2020). Bioakumulasi Logam Berat Merkuri (Hg) Pada Mangrove Jenis Rhizophora Mucronata Di Teluk Kayeli Kabupaten Buru. *Biosel: Biology Science and Education*, *9*(2), 139. https://doi.org/10.33477/bs.v9i2.1637
17. Jaiswal, K. K., Dutta, S., Banerjee, I., Pohrmen, C. B., Singh, R. K., Das, H. T., Dubey, S., & Kumar, V. (2022). Impact of aquatic microplastics and nanoplastics pollution on ecological systems and sustainable remediation strategies of biodegradation and photodegradation. *Science of the Total Environment*, *806*. https://doi.org/10.1016/j.scitotenv.2021.151358
18. Kamali, M., Persson, K. M., Costa, M. E., & Capela, I. (2019). Sustainability criteria for assessing nanotechnology applicability in industrial wastewater treatment: Current status and future outlook. *Environment International*, *125*, 261–276. https://doi.org/10.1016/j.envint.2019.01.055
19. Krisnayanti, B. D., & Anderson, C. (2014). Gold phytomining: A new idea for environmental sustainability in Indonesia. *Indonesian Journal on Geoscience*, *1*(1), 1–7. https://doi.org/10.17014/ijog.v1i1.171
20. Kumar, D., & Singh, B. (2019). Algal biorefinery: An integrated approach for sustainable biodiesel production. *Biomass and Bioenergy*, *131*. https://doi.org/10.1016/j.biombioe.2019.105398
21. Lamborg, C. H., Kent, D. B., Swarr, G. J., Munson, K. M., Kading, T., O'Connor, A. E.,

Fairchild, G. M., Leblanc, D. R., & Wiatrowski, H. A. (2013). Mercury speciation and mobilization in a wastewater-contaminated groundwater plume. *Environmental Science and Technology*, *47*(23), 13239–13249. https://doi.org/10.1021/es402441d

22. Liang, Z., Fang, W., Luo, Y., Lu, Q., Juneau, P., He, Z., & Wang, S. (2021). Mechanistic insights into organic carbon-driven water blackening and odorization of urban rivers. *Journal of Hazardous Materials*, *405*. https://doi.org/10.1016/j.jhazmat.2020.124663
23. Liu, C., Li, Y., Gai, X., Xiang, Z., Jiang, W., He, S., Liu, Y., & Xiao, H. (2023). Advances in green materials derived from wood for detecting and removing mercury ions in water. *Environmental Pollution*, *335*. https://doi.org/10.1016/j.envpol.2023.122351
24. Luong, V. T., Cañas Kurz, E. E., Hellriegel, U., Luu, T. L., Hoinkis, J., & Bundschuh, J. (2018). Iron-based subsurface arsenic removal technologies by aeration: A review of the current state and future prospects. *Water Research*, *133*, 110–122. https://doi.org/10.1016/j.watres.2018.01.007
25. M.A, A. S., El-Nour, E. A. A. A., Bassiouny, H. M. S. E.-, Abdallah, M. M. ., & A.A, A. E.-M. (2023). Mercury toxicity, molecular reaction and tolerance in plants: A review. *Middle East Journal of Applied Sciences*, *13*(3), 319–402. https://doi.org/10.36632/mejas/2023.13.3.26
26. Magazzino, C., Mele, M., Schneider, N., & Sarkodie, S. A. (2021). Waste generation, wealth and GHG emissions from the waste sector: Is Denmark on the path towards circular economy? *Science of the Total Environment*, *755*. https://doi.org/10.1016/j.scitotenv.2020.142510
27. Mahar, A., Wang, P., Ali, A., Awasthi, M. K., Lahori, A. H., Wang, Q., Li, R., & Zhang, Z. (2016). Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: A review. *Ecotoxicology and Environmental Safety*, *126*, 111–121. https://doi.org/10.1016/j.ecoenv.2015.12.023
28. Meena, M. D., Yadav, R. K., Narjary, B., Yadav, G., Jat, H. S., Sheoran, P., Meena, M. K., Antil, R. S., Meena, B. L., Singh, H. V, Singh Meena, V., Rai, P. K., Ghosh, A., & Moharana, P. C. (2019). Municipal solid waste (MSW): Strategies to improve salt affected soil sustainability: A review. *Waste Management*, *84*, 38–53. https://doi.org/10.1016/j.wasman.2018.11.020
29. Musial, J., Mlynarczyk, D. T., & Stanisz, B. J. (2023). Photocatalytic degradation of sulfamethoxazole using TiO2-based materials – Perspectives for the development of a sustainable water treatment technology. *Science of the Total Environment*, *856*. https://doi.org/10.1016/j.scitotenv.2022.159122
30. Olasanmi, I. O., & Thring, R. W. (2018). The role of biosurfactants in the continued drive for environmental sustainability. *Sustainability (Switzerland)*, *10*(12), 1–12. https://doi.org/10.3390/su10124817
31. Owusu, O., Bansah, K. J., & Mensah, A. K. (2019). "Small in size, but big in impact": Socio-environmental reforms for sustainable artisanal and small-scale mining. *Journal of Sustainable Mining*, *18*(1), 38–44. https://doi.org/10.1016/j.jsm.2019.02.001
32. Pant, G., Garlapati, D., Agrawal, U., Prasuna, R. G., Mathimani, T., & Pugazhendhi, A. (2021). Biological approaches practised using genetically engineered microbes for a sustainable environment: A review. *Journal of Hazardous Materials*, *405*. https://doi.org/10.1016/j.jhazmat.2020.124631
33. Parvaresh, H., Abedi, Z., Farshchi, P., Karami, M., Khorasani, N., & Karbassi, A. (2011). Bioavailability and concentration of heavy metals in the sediments and leaves of grey mangrove, avicennia marina (Forsk.) Vierh, in Sirik Azini creek, Iran. *Biological Trace Element Research*, *143*(2), 1121–1130. https://doi.org/10.1007/s12011-010-8891-y
34. Pörtner, H.-O., Scholes, R. J., Arneth, A., Barnes, D. K. A., Burrows, M. T., Diamond, S. E., Duarte, C. M., Kiessling, W., Leadley, P., Managi, S., McElwee, P., Midgley, G., Ngo, H. T., Obura, D., Pascual, U., Sankaran, M., Shin, Y. J., & Val, A. L. (2023). Overcoming the coupled climate and biodiversity crises and their societal impacts. *Science*, *380*(6642). https://doi.org/10.1126/science.abl4881
35. Putra, P. H. M., Rozali, S., Patah, M. F. A., & Idris, A. (2022). A review of microwave

pyrolysis as a sustainable plastic waste management technique. *Journal of Environmental Management*, *303*. https://doi.org/10.1016/j.jenvman.2021.114240
36. Putri, R. W. P., Hariani, P. L., & Arifin, Z. (2023). Biokonsentrasi Faktor (BCF) dan Faktor Translokasi (TF) Purun tikus (Eleocharis dulcis) dalam Fitoremediasi Air Asam Tambang. *Jurnal Pengendalian Pencemaran Lingkungan (JPPL)*, *5*(1), 76–82. https://doi.org/10.35970/jppl.v5i1.1832
37. Raheem, I., Mubarak, N. M., Karri, R. R., Solangi, N. H., Jatoi, A. S., Mazari, S. A., Khalid, M., Tan, Y. H., Koduru, J. R., & Malafaia, G. (2023). Rapid growth of MXene-based membranes for sustainable environmental pollution remediation. *Chemosphere*, *311*. https://doi.org/10.1016/j.chemosphere.2022.137056
38. Ravichandran, M. (2004). Interactions between mercury and dissolved organic matter - A review. *Chemosphere*, *55*(3), 319–331. https://doi.org/10.1016/j.chemosphere.2003.11.011
39. Sabra, M., Aboulnasr, A., Franken, P., Perreca, E., Wright, L. P., & Camehl, I. (2018). Beneficial root endophytic fungi increase growth and quality parameters of sweet basil in heavy metal contaminated soil. *Frontiers in Plant Science*, *871*(November), 1–13. https://doi.org/10.3389/fpls.2018.01726
40. Schröder, P., Lemille, A., & Desmond, P. (2020). Making the circular economy work for human development. *Resources, Conservation and Recycling*, *156*. https://doi.org/10.1016/j.resconrec.2020.104686
41. Shahrajabian, M. H., Chaski, C., Polyzos, N., Tzortzakis, N., & Petropoulos, S. A. (2021). Sustainable agriculture systems in vegetable production using chitin and chitosan as plant biostimulants. *Biomolecules*, *11*(6), 1–18. https://doi.org/10.3390/biom11060819
42. Takarina, N. D., & Pin, T. G. (2017). Bioconcentration Factor (BCF) and Translocation Factor (TF) of Heavy Metals in Mangrove Trees of Blanakan Fish Farm. *Makara Journal of Science*, *21*(2), 77–81. https://doi.org/10.7454/mss.v21i2.7308
43. Tian, W., Egeland, G. M., Sobol, I., & Chan, H. M. (2011). Mercury hair concentrations and dietary exposure among Inuit preschool children in Nunavut, Canada. *Environment International*, *37*(1), 42–48. https://doi.org/10.1016/j.envint.2010.05.017
44. Usman, K., Al Jabri, H., Abu-Dieyeh, M. H., & Alsafran, M. H. S. A. (2020). Comparative Assessment of Toxic Metals Bioaccumulation and the Mechanisms of Chromium (Cr) Tolerance and Uptake in Calotropis procera. *Frontiers in Plant Science*, *11*(June), 1–11. https://doi.org/10.3389/fpls.2020.00883
45. Vangronsveld, J., Herzig, R., Weyens, N., Boulet, J., Adriaensen, K., Ruttens, A., Thewys, T., Vassilev, A., Meers, E., Nehnevajova, E., van der Lelie, D., & Mench, M. (2009). Phytoremediation of contaminated soils and groundwater: Lessons from the field. In *Environmental Science and Pollution Research* (Vol. 16, Issue 7). https://doi.org/10.1007/s11356-009-0213-6
46. Winton, D. J., Anderson, L. G., Rocliffe, S., & Loiselle, S. (2020). Macroplastic pollution in freshwater environments: Focusing public and policy action. *Science of the Total Environment*, *704*. https://doi.org/10.1016/j.scitotenv.2019.135242
47. Yang, M., Chen, L., Msigwa, G., Tang, K. H. D., & Yap, P.-S. (2022). Implications of COVID-19 on global environmental pollution and carbon emissions with strategies for sustainability in the COVID-19 era. *Science of the Total Environment*, *809*. https://doi.org/10.1016/j.scitotenv.2021.151657
48. Yang, T., Ren, L., Jia, Y., Fan, S., Wang, J., Wang, J., Nahurira, R., Wang, H., & Yan, Y. (2018). Biodegradation of Di-(2-ethylhexyl) phthalate by rhodococcus ruber YC-YT1 in contaminated water and soil. *International Journal of Environmental Research and Public Health*, *15*(5). https://doi.org/10.3390/ijerph15050964
49. Yao, Z., Seong, H. J., & Jang, Y.-S. (2022). Environmental toxicity and decomposition of polyethylene. *Ecotoxicology and Environmental Safety*, *242*. https://doi.org/10.1016/j.ecoenv.2022.113933
50. Yoon, J., Cao, X., Zhou, Q., & Ma, L. Q.

(2006). Accumulation of Pb, Cu, and Zn in native plants growing on a contaminated Florida site. *Science of the Total Environment*, *368*(2–3), 456–464. https://doi.org/10.1016/j.scitotenv.2006.01.016

51. Yu, S., Wang, X., Pang, H., Zhang, R., Song, W., Fu, D., Hayat, T., & Wang, X. (2018). Boron nitride-based materials for the removal of pollutants from aqueous solutions: A review. *Chemical Engineering Journal*, *333*, 343–360. https://doi.org/10.1016/j.cej.2017.09.163
52. Zam, Z. Z., & Saleh, M. (2022). *Artificial intelligence (AI) dalam perhitungan kuantum : studi in-silico penggunaan kitosan sebagai bio-sensor limbah merkuri di perairan sekitar tambang di Maluku Utara*. 1–11.
53. Zheng, Y., Li, G., Jiang, J., Zhang, L., & Yue, T. (2024). Application Study on the Activated Coke for Mercury Adsorption in the Nonferrous Smelting Industry. *Sustainability (Switzerland)*, *16*(1). https://doi.org/10.3390/su16010421