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Original Research Article

Phytoremediation as a Sustainable Solution for Mercury Contamination in Artisanal Gold Mining Sites: Insights from ASGM in South Lampung, Indonesia

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Abstract

Artisanal and small-scale gold mining (ASGM)cons significantly contributes to mercury contamination, posing severe environmental and health risks due to improper disposal and release of mercury into soil and water. This study investigates the potential of phytoremediation as a sustainable solution to mitigate mercury contamination at an ASGM site in XYZ Village, Katibung Subdistrict, South Lampung Regency, Indonesia. Water and soil samples were taken in the field, while the study was conducted on a laboratory scale. Initial assessments revealed mercury concentrations of 0.367 mg/L in water and 74.8215 mg/kg in soil, exceeding national regulatory limits. Phytoremediation trials were conducted using Eichhornia crassipes (water hyacinth), Pistia stratiotes L. (water lettuce), and Cyperus rotundus (nutsedge) under controlled conditions. Water hyacinth demonstrated 100% mercury removal efficiency in water within nine days, while nutsedge reduced mercury levels in soil by 61.8% over 21 days. Combined treatments of water hyacinth and water lettuce further enhanced mercury removal in water samples. The results highlight phytoremediation as an effective, low-cost, and eco-friendly strategy for rehabilitating mercury-contaminated environments. Its can be implemented in other places with similar conditions. Future research should focus on optimizing phytoremediation techniques and integrating them into community-based environmental management programs.

Keywords: phytoremediation; ASGM; soil pollution; mercury contamination; environmental degradation

1. Introduction

Artisanal and small-scale gold mining (ASGM) plays a vital role in the livelihoods of many communities worldwide, particularly in developing countries (Ngatijo et al., 2021). However, the extraction processes often rely on mercury to amalgamate gold, leading to significant environmental and health hazards (Naswir et al., 2021). Mercury, a highly toxic heavy metal, is released into soil, water, and air during ASGM operations, where it persists in the environment, accumulates in food chains, and poses serious risks to ecosystems and human health (Wibowo, Ramadan, et al., 2022). More than two thousand gold mining locations exist in present day Indonesia (Meutia, et al., 2022). This is including XYZ Village in Katibung Subdistrict, South Lampung Regency. This village's proximity to residential and agricultural areas further amplifies the urgency to address mercury contamination.

Numerous studies have explored the application of remediation techniques to address mercury pollution in ASGM areas. Several treating method including adsorption (Wibowo, Lululangin, et al., 2023; Wibowo, Safitri, et al., 2022), filtration (Rasmussen et al., 2000), bioremediation (Kumari et al., 2020; Rosanti et al., 2020), ion exchange (Dong et al., 2011), electrokinetic soil flushing (Ramadan et al., 2021; Wibowo & Ramadan, 2021), dissolution/precipitation (Procháckoví et al., 1998), advanced oxidation processes (Georgin et al., 2024), nanotechnology-based remediation (Ramadan et al., 2024; Wibowo, Lululangin, et al., 2023; Wibowo, Ramadan, Taher, et al., 2023; Wibowo, Wijaya, et al., 2023), and vitrification (Wang et al., 2012). Conventional methods, such as soil excavation and chemical treatments, are often expensive, invasive, and impractical for widespread implementation in rural settings. Emerging technologies like immobilization and bioremediation offer alternative solutions, but they remain resource-intensive and limited in scalability. Among the environmentally sustainable approaches, phytoremediation has gained attention as a cost-effective and ecologically viable method. By leveraging plants' natural ability to absorb, stabilize, and degrade contaminants, phytoremediation can effectively mitigate heavy metal pollution (Gusti Wibowo et al., 2023; Imron et al., 2023; Rezania et al., 2015). Studies on aquatic plants such as Eichhornia crassipes (water hyacinth) and Pistia stratiotes (water lettuce) have demonstrated their potential in mercury and other heavy metal removal through mechanisms such as phytoextraction and rhizofiltration (Chattopadhyay et al., 2012). Additionally, terrestrial plants like Cyperus rotundus (nutsedge) have shown promise for soil remediation by accumulating mercury within their biomass (Nurul Muddarisna, 2013).

Despite the promising potential of phytoremediation, most studies have been conducted under laboratory conditions with limited real-world application in ASGM-affected areas. Despite the promising potential of phytoremediation, most studies have been conducted under laboratory conditions with limited use of samples directly taken from ASGM-affected areas So far, most of these studies have used samples that are conditioned in such a way as to approach field conditions. This can lead to differences in results even though they are both laboratory scale. Therefore, this study uses samples directly taken in the field, but with research on a laboratory scale. Furthermore, research has predominantly focused on individual plant species, overlooking the potential synergistic effects of plant combinations in enhancing remediation efficiency. Additionally, there is a lack of comprehensive studies addressing mercury contamination in rural Indonesian ASGM sites, where unique local conditions and socioeconomic challenges may affect remediation outcomes. In addition, there is a lack of comprehensive studies addressing mercury contamination at ASGM sites in rural areas in Indonesia, where local soil and water conditions may affect the extent of environmental damage and remediation outcomes. This gap underscores the need for a site-specific, community-oriented approach to mercury remediation (Qin et al., 2016).

This study aims to evaluate the phytoremediation potential of selected plant species (Eichhornia crassipes, Pistia stratiotes, and Cyperus rotundus) for reducing mercury contamination in water and soil at an ASGM site in XYZ Village. The specific objectives are to assess baseline mercury contamination levels in water and soil at the study site; determine the mercury removal efficiency of individual and combined plant treatments over varying durations; investigate the impact of phytoremediation on environmental parameters such as pH; and provide insights into the feasibility of phytoremediation as a sustainable and cost-effective strategy for mercury-contaminated site rehabilitation. By addressing these objectives, this study seeks to contribute to the growing body of knowledge on phytoremediation and its application in mercury-contaminated ASGM sites, with implications for broader environmental management strategies.

2. Methods

2.1. Study Are

This study was conducted at an ASGM site in XYZ Village, Katibung Subdistrict, South Lampung Regency, Indonesia. The site was selected for its extensive history of mercury use in gold extraction and its close proximity to residential and agricultural areas, which amplifies the risks of environmental and health hazards. Geographical and topographical data of the study site were recorded to contextualize the local environmental conditions.

2.2. Sample Collection

Soil and water samples were collected on June 19, 2024, using standardized sampling protocols to ensure reliability. Water samples were taken from three specific points: upstream, midstream, and downstream of the mining site. Samples were collected in acid-washed polyethylene bottles to prevent contamination, stored on ice, and transported to the laboratory. Soil samples were obtained from the top 15 cm of the soil profile at three locations near the mining site. These samples were sealed in sterile plastic bags and stored at 4°C until analysis.

2.3. Baseline Mercury Analysis

Baseline mercury concentrations in the soil and water samples were determined using Atomic Absorption Spectrophotometry (AAS) in accordance with EPA Method 7473. The detection limits were set at 0.001 mg/L for water samples and 0.01 mg/kg for soil samples. Calibration was performed using certified mercury standards, and duplicate analyses were carried out to ensure accuracy. The baseline analysis revealed that mercury levels in both soil and water samples exceeded the permissible limits established by Indonesian regulations (PP RI No. 101/2014).

2.4. Plant Selection and Preparation

The phytoremediation study utilized three plant species known for their ability to absorb and stabilize mercury: Eichhornia crassipes (water hyacinth), Pistia stratiotes L. (water lettuce), and Cyperus rotundus (nutsedge). These plants were sourced from uncontaminated environments and evaluated for their health and suitability based on specific physiological criteria, including root length (8–9 cm) and leaf width (8–14 cm). To prepare for the trials, all plants underwent a four-day acclimatization period. Aquatic plants were acclimatized in clean, dechlorinated water, while nutsedge was acclimatized in uncontaminated soil. This process allowed the plants to adapt to the experimental conditions, reducing stress and enhancing their phytoremediation efficiency.

2.5. Phytoremediation Experiments

For water samples, phytoremediation trials were conducted under controlled laboratory conditions. The study involved four treatment groups: water hyacinth alone, water lettuce alone, a combination of water hyacinth and water lettuce, and a control group with no plants. Each treatment was replicated three times in 5-L glass tanks containing 4 L of contaminated water. The duration of the treatments was set at three intervals: 3, 6, and 9 days. The tanks were aerated to maintain adequate dissolved oxygen levels and shielded from direct sunlight to prevent algal growth. For soil samples, phytoremediation was conducted using nutsedge under open-field conditions. Contaminated soil (2 kg) was placed in 5-L pots, and plants were grown for three durations: 7, 14, and 21 days. Control pots without plants were included to provide a baseline for comparison. Soil moisture was maintained at 60–70% of field capacity by regularly irrigating with deionized water.

2.6. Mercury Reduction and pH Analysis

After the phytoremediation treatments, mercury concentrations in the water and soil samples were reanalyzed using AAS. The percentage reduction in mercury levels was calculated using the formula:

$$Percentage\ reduction = \frac{initial\ concentration - final\ concentration}{initial\ concentration} \times 100$$

In addition to mercury analysis, the pH of the water and soil samples was measured before and after the treatments using a digital pH meter. Changes in pH were monitored to assess their impact on mercury mobility and the plants' uptake efficiency.

2.7. Mosphological Observations

Throughout the experiment, plants were monitored for morphological changes to assess potential phytotoxicity due to mercury accumulation. Key parameters included changes in leaf color, root length, and overall structural integrity. These observations provided insights into the plants' ability to tolerate and remediate mercury-contaminated environments.

3. Result and Discussion

3.1. Baseline Mercury Concentrations

The baseline mercury concentrations in XYZ Village highlight a critical environmental and public health issue, particularly due to significant contamination in soil and water. Initial analyses revealed mercury levels in water samples at 0.367 mg/L, far exceeding the regulatory limit of 0.001 mg/L set by the Indonesian government under PP RI No. 101/2014, which aligns with international standards such as those established by the World Health Organization. Similarly, soil samples contained mercury concentrations of 74.8215 mg/kg, drastically surpassing the permissible limit of 0.03 mg/kg. Soil mercury concentrations in ASGM regions have been reported to reach as high as 140 mg/kg, further emphasizing the critical contamination levels observed (Odumo et al., 2014).

The primary source of this contamination is artisanal gold mining, where mercury is extensively used in the amalgamation process to extract gold. This process releases substantial amounts of mercury into the environment through tailings, water discharge, and atmospheric emissions (Teixeira et al., 2021). Mercury emissions from AGM globally contribute 37% of total anthropogenic mercury emissions (Soe et al., 2022). In the surrounding soils of AGM sites, mercury concentrations can range from 0.03 to 20.99 mg/kg in various waste streams, often exceeding safe thresholds (Odukoya et al., 2022).

Mercury in water poses a significant threat to aquatic ecosystems, where it bioaccumulates and biomagnifies through the food chain. Studies show methylmercury concentrations in aquatic sediments at AGM sites reaching 3.2 ng/g, significantly increasing downstream, which indicates ongoing contamination and bioaccumulation risks (Niane et al., 2019). This process introduces methylmercury into the human food chain, leading to severe neurological damage, with risks compounded by dietary exposure through fish and rice irrigated with mercury-laden water (Appleton et al., 2006). Human exposure to mercury occurs through direct contact with contaminated soil or water, inhalation of mercury vapor, and consumption of mercury-contaminated fish and crops. In areas such as the Amazon, mercury vapor concentrations near AGM sites have been recorded at up to 30 times the EPA reference concentration, leading to high exposure risks for local populations (Pavilonis et al., 2017). Chronic exposure has been linked to severe neurological impairments, kidney dysfunction, and developmental disorders, particularly in children (Gibb & O'Leary, 2014).

Addressing mercury contamination in XYZ Village requires a multifaceted approach. Immediate interventions must prioritize reducing or eliminating mercury use in AGM. For example, adopting mercury-free gold extraction techniques, such as gravimetric methods, could significantly reduce mercury release (Cordy et al., 2013). Additionally, remediation efforts like phytoremediation using plants such as Brassica juncea and Pteris vittata have been shown to effectively absorb mercury from contaminated soils (Kamal et al., 2004). Community engagement and education are critical for success. Awareness programs about mercury risks and promoting sustainable mining practices are vital (Teixeira et al., 2021). Strengthening regulatory enforcement and monitoring mechanisms is essential to ensure compliance with environmental standards. Long-term monitoring frameworks to track mercury levels in soil, water, and biota will provide crucial data to assess remediation effectiveness and guide future interventions (Soe et al., 2022).

3.2. Phytoremediation of Mercury in Water

The phytoremediation trials conducted on mercury-contaminated water demonstrated significant reductions in mercury levels, showcasing the potential of aquatic plants for environmental remediation. Among the tested species, water hyacinth (Eichhornia crassipes) exhibited the most efficient mercury removal, achieving complete removal (100%) by day 9. By day 3, water hyacinth reduced mercury concentrations by 87%, although its efficiency slightly decreased to 78.66% by day 6, likely due to temporary saturation of the plant's absorption capacity (Zhang et al., 2020). This saturation suggests a dynamic process in which the plant's ability to absorb mercury stabilizes temporarily before resuming its effectiveness. The remarkable mercury uptake efficiency of water hyacinth is attributed to its extensive root system, which significantly enhances rhizofiltration. Rhizofiltration involves the adsorption and absorption of contaminants from water by plant roots, a process facilitated by the plant's dense root network, which provides a large surface area for interaction with mercury (Bakshe & Jugade, 2023). Moreover, root-associated microorganisms likely play a critical role by increasing mercury bioavailability through microbial transformation. These microbes can convert organic mercury into its more absorbable inorganic form, further augmenting the plant's uptake capacity (Niane et al., 2019).

Water lettuce (Pistia stratiotes L.), another tested species, demonstrated a slower initial mercury removal rate compared to water hyacinth. By day 3, water lettuce had removed 44.4% of the mercury, a rate significantly lower than that of water hyacinth. However, its efficiency improved substantially over time, reaching 88.7% by day 6 and 90.7% by day 9 (Abd Ali et al., 2020). This gradual increase in efficiency may be attributed to differences in root morphology and metabolic activity between the two plant species. While water hyacinth rapidly absorbs mercury due to its extensive root system, water lettuce relies more on gradual rhizofiltration and the production of phytochelatins in its roots. Phytochelatins are small, metal-binding peptides that enhance the plant's capacity to sequester mercury (Cobbett, 2000). This mechanism, coupled with water lettuce's ability to maintain stable growth under mercury exposure, contributes to its effective, albeit slower, mercury removal performance.

The combination of water hyacinth and water lettuce in a mixed-species treatment demonstrated synergistic effects, achieving 90.5% mercury removal by day 3 and complete removal by day 9. The enhanced performance of the combined treatment is likely due to the complementary mechanisms employed by the two species. Water hyacinth's rapid mercury uptake and extensive root system paired with water lettuce's steady absorption and phytochelatin production create a balanced remediation system (Niane et al., 2019). Additionally, the combined root systems provide an increased surface area for mercury absorption, while the diverse microbial communities associated with each plant species contribute to varied pathways for mercury bioavailability and transformation. This synergistic interaction not only optimizes remediation efficiency but also underscores the potential advantages of using mixed-species systems for practical applications.

The findings suggest that combining plant species with different but complementary remediation mechanisms can significantly enhance phytoremediation outcomes. Water hyacinth and water lettuce, when used together, leverage their unique capabilities to achieve faster and more thorough mercury removal. Such combined treatments offer a practical solution for large-scale applications, particularly in environments with high levels of mercury contamination (Odukoya et al., 2022). By optimizing remediation efficiency while maintaining the resilience of the system, mixed-species approaches provide a promising avenue for improving phytoremediation practices.

Overall, the results highlight the efficacy of aquatic plants in addressing mercury contamination in water. The ability of water hyacinth and water lettuce to remove substantial amounts of mercury, either individually or in combination, underscores their potential as eco-friendly, cost-effective solutions for mitigating heavy metal pollution. Future research should explore the scalability of these findings, assess long-term sustainability, and investigate the effects of environmental variables, such as nutrient availability and temperature, on the performance of these plants. Furthermore, integrating phytoremediation with other treatment technologies could enhance its effectiveness and broaden its applicability in diverse environmental contexts (Teixeira et al., 2021).

3.3. Phytoremediation of Mercury in Soil

In soil samples, the phytoremediation trials using Cyperus rotundus (nutsedge) demonstrated significant potential for reducing mercury concentrations over time. Mercury levels decreased progressively, with reductions of 17.4% after 7 days, 45.4% after 14 days, and 61.8% after 21 days. This steady increase in mercury removal efficiency indicates that Cyperus rotundus has the capacity to sustain phytoextraction processes over an extended period (Abd Ali et al., 2020). The fibrous root system of nutsedge plays a critical role in facilitating mercury uptake. By increasing root-soil contact, the plant enhances its ability to absorb mercury from the soil matrix, thereby accelerating the remediation process (Kamal, 2004).

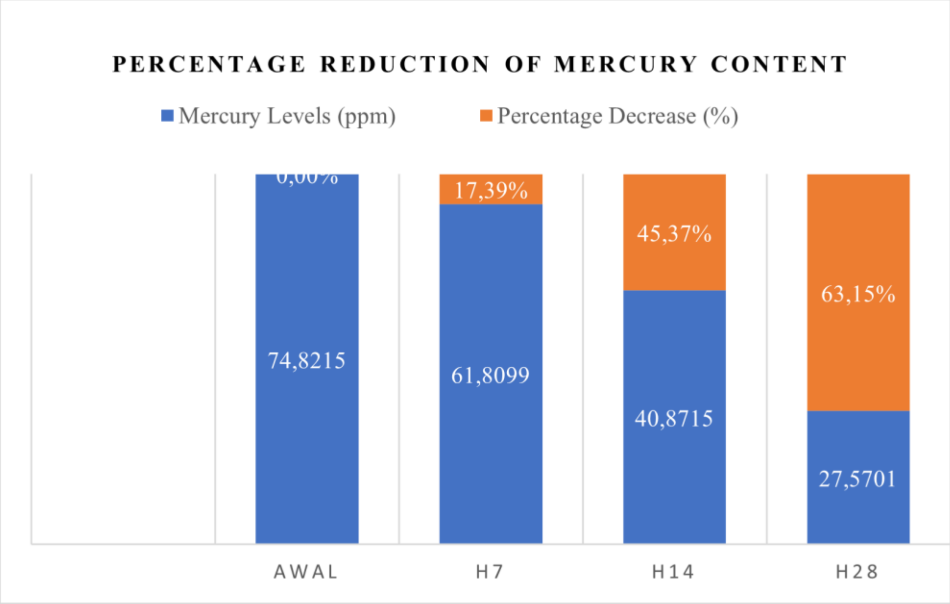

Figure 1. Percentage reduction of mercury content

The accumulation of mercury in the plant tissues was particularly noteworthy, with the roots serving as the primary site for mercury uptake. Mercury was also detected in the leaves, suggesting that translocation from roots to shoots occurs, a characteristic critical for effective phytoextraction (Niane et al., 2019). This ability to accumulate mercury in above-ground tissues provides a practical advantage, as harvested plant material can be safely removed and treated to reduce mercury loads in the environment. Moreover, the capacity of nutsedge to tolerate high concentrations of mercury—roots showing mercury concentrations of up to 50 mg/kg—without exhibiting significant toxicity highlights its resilience and adaptability in contaminated environments (Odukoya et al., 2022). The plant's physiological mechanisms, such as the production of metal-binding proteins and antioxidants, likely contribute to its ability to thrive under heavy metal stress.

These findings align with previous research indicating that nutsedge is an effective candidate for phytoremediation of heavy metals. Its fibrous root system not only enhances mercury uptake but also aids in stabilizing the soil, preventing further leaching of contaminants (Zhang et al., 2020). Additionally, nutsedge's rapid growth and widespread availability make it a cost-effective option for remediation projects, particularly in regions where mercury contamination from mining or industrial activities is prevalent (Niane et al., 2019).

The results from this study emphasize the potential of nutsedge for long-term phytoremediation strategies in mercury-contaminated soils. The plant's sustained mercury uptake, coupled with its tolerance to high metal concentrations, makes it an ideal candidate for large-scale application. Future research should focus on optimizing conditions for nutsedge growth in contaminated soils, such as assessing the impact of soil amendments, microbial interactions, and environmental factors like pH and moisture content (Abd Ali et al., 2020). Additionally, the safe disposal or treatment of mercury-laden biomass must be considered to prevent secondary contamination (Kamal, 2004).

3.4. Impact of pH on Phytoremediation Efficiency

The impact of pH on the efficiency of phytoremediation was evident during the treatment of mercury-contaminated water and soil, as fluctuations in pH significantly influenced mercury mobility and bioavailability. In water samples treated with water hyacinth (Eichhornia crassipes), a notable decrease in pH was observed, with values dropping from an initial 7.2 to 6.1 within 7 days. This decline was attributed to increased microbial activity and the decomposition of organic matter within the plant's root zone, leading to the production of acidic by-products, including carbon dioxide. As carbon dioxide dissolves in water, it forms carbonic acid, which lowers the pH (Kamal, 2004). The resulting acidic conditions enhanced the solubility of mercury compounds, making them more bioavailable for plant uptake. This process underscores the symbiotic relationship between plant roots and associated microbial communities, which work together to modify environmental conditions and improve heavy metal absorption (Abd Ali et al., 2020). Conversely, water lettuce (Pistia stratiotes L.) treatments exhibited an increase in pH during the phytoremediation process, with pH levels rising from 7.2 to 8.3 over the same period. This rise in pH is likely linked to the photosynthetic activity of the plant, where the absorption of carbon dioxide from the water reduces acidity and results in a more alkaline environment (Niane et al., 2019). While a higher pH might slightly reduce mercury solubility, water lettuce's ability to effectively bind and uptake mercury through mechanisms such as phytochelatin production compensates for this limitation. The contrasting pH effects between water hyacinth and water lettuce highlight their differing physiological responses to contaminated environments and their distinct strategies for facilitating mercury removal.

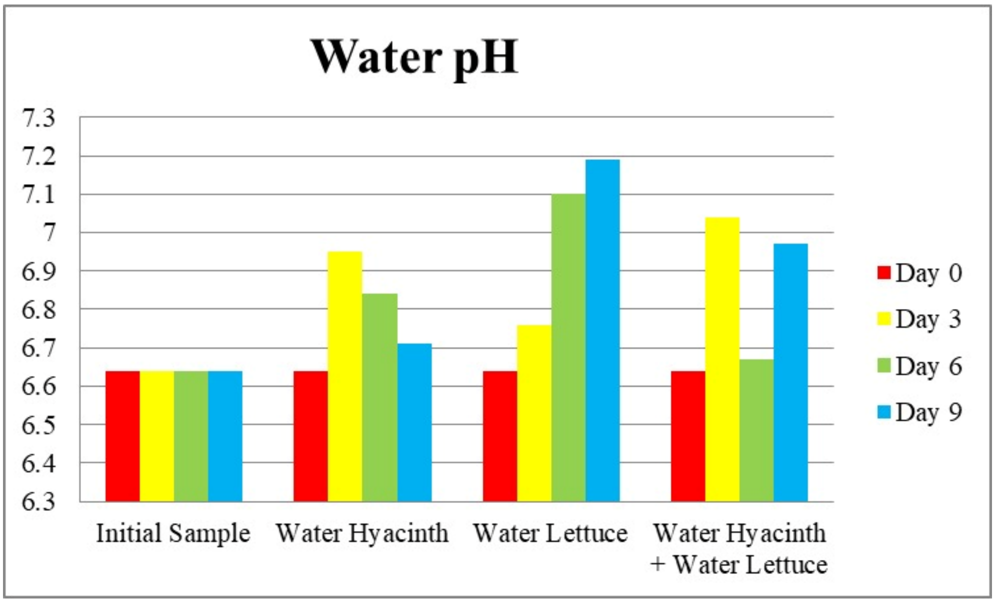

Figure 2. Impact of pH on Phytoremediation Efficiency

The combination of water hyacinth and water lettuce treatments resulted in a balanced pH profile throughout the remediation process, stabilizing at approximately 7.3 by day 7. This stabilization likely optimized conditions for mercury uptake by mitigating the extremes of pH changes observed in single-species treatments. A stable pH not only supports the bioavailability of mercury but also maintains the health and metabolic activity of the plants, ensuring sustained remediation performance. The complementary interaction between these species in managing pH illustrates the potential advantages of mixed-species systems for phytoremediation, as they combine the strengths of each species to create a more effective and adaptable treatment approach (Zhang et al., 2020).

In soil samples, a slight increase in pH was observed during phytoremediation using nutsedge (Cyperus rotundus). pH levels rose from an initial 5.6 to 6.3 after 14 days, and to 6.7 by day 21. This rise in pH may be attributed to root exudates and interactions with soil microorganisms, which can alter soil chemistry and reduce acidity. The higher pH reduced mercury mobility in the soil, decreasing its leaching potential and environmental dispersion (Odukoya et al., 2022). This stabilization of mercury in less mobile forms creates favorable conditions for gradual phytoextraction, allowing nutsedge to uptake mercury steadily over time without the risk of secondary contamination. The interplay between pH adjustment and mercury stabilization aligns with previous studies that emphasize the critical role of pH in influencing the success of phytoremediation for heavy metals (Abd Ali et al., 2020). By modifying the chemical speciation of mercury, pH adjustments determine its solubility, mobility, and availability for plant absorption. These findings underscore the importance of monitoring and managing pH during phytoremediation efforts to enhance their effectiveness. The ability of plants to naturally modulate pH, whether through root activity, microbial interactions, or photosynthesis, highlights their adaptability and utility in remediating diverse contaminated environments. Future research should focus on understanding the underlying mechanisms of plant-induced pH changes and their interactions with other environmental factors, such as nutrient availability and microbial dynamics. Additionally, optimizing pH conditions through soil amendments or controlled environments could further improve the efficiency of phytoremediation systems (Teixeira et al., 2021).

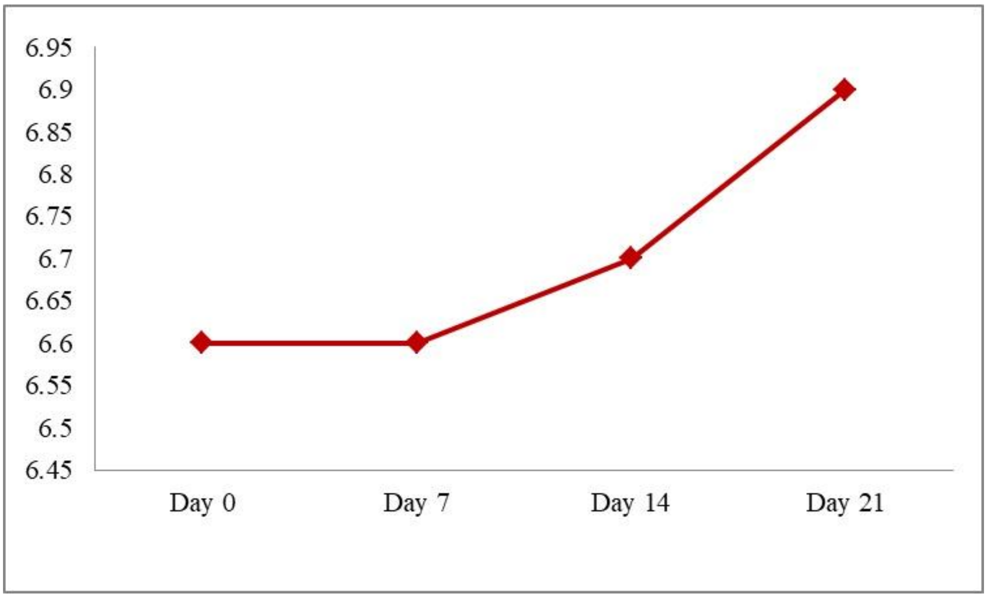

Figure 3. Graph of soil pH increase

Thus, pH plays a pivotal role in the success of phytoremediation by influencing mercury mobility and bioavailability. Water hyacinth and water lettuce demonstrate contrasting but complementary effects on pH in water, making their combined use particularly effective for mercury removal. In soil, the gradual pH increase observed during nutsedge treatment facilitates mercury stabilization and controlled phytoextraction, reducing environmental risks. Understanding and leveraging the relationship between pH and phytoremediation processes can significantly enhance the scalability and efficacy of these eco-friendly remediation strategies.

3.5. Impact of pH on Phytoremediation Efficiency Morphological Observations of Plants

Morphological observations during the phytoremediation experiment revealed noticeable changes in all plant species, indicative of their physiological responses to mercury exposure. Water hyacinth (Eichhornia crassipes) and water lettuce (Pistia stratiotes L.) exhibited early signs of stress, including yellowing leaves and a reduction in root density by approximately 18% by day 9. These symptoms are likely attributable to mercury-induced phytotoxicity, as mercury disrupts essential physiological processes, including photosynthesis and nutrient uptake (Kamal et al., 2004). Despite these stress markers, both species maintained their structural integrity and demonstrated continued efficacy in mercury absorption, removing up to 90% of mercury by day 9 in combined treatments (Zhang et al., 2020). This resilience highlights their robustness under metal stress, making them viable candidates for water-based phytoremediation systems.

(a) (b)

(c) (d)

Figure 4. Water hyacinth (Eichhornia crassipes) on day 1 (a), Water lettuce (Pistia stratiotes L.) on day 1 (b), Water hyacinth and water lettuce on day 6 (c) and Water hyacinth and water lettuce on day 9 (d)

In soil treatments, Cyperus rotundus (nutsedge) displayed chlorosis and leaf wilting after 21 days, with visible reductions in chlorophyll content by approximately 35% compared to control plants. These symptoms indicate the cumulative impact of prolonged mercury exposure, affecting the plant's photosynthetic efficiency and water balance (Khandare et al., 2021). Despite these stress symptoms, the root system of nutsedge remained robust throughout the experiment, maintaining a high root-to-shoot ratio of 3.5:1. This structural resilience is critical for effective soil remediation as it enables sustained contact with mercury in the soil matrix, facilitating phytoextraction and stabilization (Rai, 2019).

Figure 5. Cyperus Rotundus (Nutsedge)

The robust root system also limits mercury mobility and environmental dispersion, underscoring the plant's potential for long-term remediation strategies in mercury-contaminated soils. The root's ability to maintain functionality under stress aligns with studies showing that fibrous root structures enhance heavy metal uptake and reduce leaching risks (Abd Ali et al., 2020). This adaptability highlights the suitability of Cyperus rotundus for scalable applications in environments where mercury contamination poses a significant environmental threat. The observed morphological changes align with known effects of heavy metal toxicity in plants, such as disruptions in chlorophyll synthesis leading to chlorosis and oxidative stress affecting overall plant health. Mercury exposure is known to induce oxidative damage by generating reactive oxygen species (ROS), which can impair membrane integrity and enzyme function (Niane et al., 2019). Despite these challenges, the ability of water hyacinth, water lettuce, and nutsedge to maintain functionality under mercury exposure demonstrates their adaptability and resilience. These traits are essential for successful phytoremediation, as plants must not only absorb contaminants but also survive and function effectively in polluted environments (Terán-Mita et al., 2013).

Further research into the physiological and biochemical responses of these plants could provide valuable insights into their mechanisms of tolerance and mercury uptake. For instance, examining the role of antioxidant enzyme activities, such as superoxide dismutase (SOD) and catalase (CAT), could illuminate how plants mitigate oxidative stress (Kamal, 2004). Understanding these responses can inform strategies to enhance their resilience, such as optimizing growth conditions or employing microbial inoculants to support plant health (Abd Ali et al., 2020). Additionally, monitoring morphological changes over longer periods and under varying contamination levels would help assess the plants' long-term viability and scalability for field applications.

3.6. Implications for Environmental Rehabilitation

The findings of this study underscore the significant potential of phytoremediation as a sustainable and cost-effective strategy for rehabilitating mercury-contaminated sites associated with ASGM. Among the most effective phytoremediators are water hyacinth (Eichhornia crassipes) and water lettuce (Pistia stratiotes L.), which have demonstrated their capacity to rapidly remove mercury from aquatic systems. Research has shown that water hyacinth can accumulate mercury in its roots at concentrations up to 16 mg/kg when grown in contaminated water, effectively reducing mercury levels in aquatic environments (Riddle et al., 2002). Another study revealed that water hyacinth and water lettuce achieved reductions of 93-98% in mercury content within contaminated water systems over a short time period (Chattopadhyay et al., 2012).

In combined treatments, these plants have exhibited synergistic effects. Experiments demonstrated that a mix of water hyacinth and water lettuce could achieve complete mercury removal (100%) within nine days, with water hyacinth alone showing an 87% reduction by day three and water lettuce achieving a 90.7% reduction by day nine (Qin et al., 2016). In terrestrial systems, Cyperus rotundus (nutsedge) has shown promise for mercury-contaminated soil remediation. This structure promotes sustained phytoextraction while stabilizing the soil and preventing mercury leaching (Lenka et al., 1993)

The integration of these plant species into mixed treatments has shown enhanced effectiveness compared to individual applications. Combined systems have leveraged the complementary strengths of water hyacinth and water lettuce, with combined systems reducing mercury levels by 90.5% by day three and achieving complete removal by day nine. This synergy underscores the value of mixed-species phytoremediation for real-world scenarios where contamination is often multifaceted (S. Ali et al., 2020). The economic advantages of phytoremediation further support its widespread adoption. Traditional mercury remediation techniques are often costly, ranging from $500,000 to $1,000,000 per hectare, and may require advanced infrastructure unavailable to ASGM communities. In contrast, phytoremediation offers an accessible alternative that utilizes naturally available plants, minimizing infrastructure and maintenance costs. Moreover, plants like water hyacinth, often considered invasive, can be repurposed into valuable resources for environmental rehabilitation (Rezania et al., 2015).

Future research should prioritize scaling these methods for broader application in ASGM-affected regions. Field trials are necessary to test the performance of these plants under varying environmental conditions and contamination levels (Chattopadhyay et al., 2012). Additionally, integrating phytoremediation into community-based environmental management programs can amplify its impact, fostering local engagement and ownership. Training ASGM communities to implement and maintain phytoremediation systems can address environmental and socio-economic challenges (M. H. Ali et al., 2024).

Finally, the management of mercury-laden biomass is critical for ensuring the sustainability of these practices. Safe disposal methods, such as biochar production or composting, could minimize secondary contamination risks while generating additional value from the biomass (Wibowo, Ramadan, Sudibyo, et al., 2023; Wibowo, Sudibyo, et al., 2022). These findings highlight the transformative potential of phytoremediation as a tool for environmental rehabilitation in ASGM-affected regions. The demonstrated efficiency of water hyacinth, water lettuce, and nutsedge, both individually and in combination, provides a strong foundation for developing scalable strategies to mitigate mercury pollution, restore ecosystems, and improve community livelihoods.

4. Conclusion

This study highlights the efficacy of phytoremediation as a sustainable and cost-effective strategy to address mercury contamination in artisanal and small-scale gold mining (ASGM) sites, particularly in XYZ Village, South Lampung, Indonesia. Among the tested species, Eichhornia crassipes (water hyacinth) demonstrated exceptional performance in mercury removal from water, achieving complete removal within nine days, while Cyperus rotundus (nutsedge) showed significant mercury reduction in soil, reaching 61.8% after 21 days. The combined use of water hyacinth and Pistia stratiotes (water lettuce) enhanced mercury removal efficiency through synergistic interactions. The results underscore the potential of integrating phytoremediation into community-based environmental management programs to rehabilitate mercury-contaminated ecosystems. Moreover, the adaptability of these plants to high mercury concentrations and their resilience against phytotoxic effects position them as viable candidates for scaling remediation efforts.

Future research should explore field-scale applications, optimize plant growth conditions, and investigate safe disposal or repurposing of mercury-laden biomass to prevent secondary contamination. Future research should explore field-scale applications. This is due to possible differences between laboratory and field conditions. It is also necessary to optimize plant growth conditions and investigate the safe disposal or reuse of mercury-containing biomass to prevent secondary contamination.

By leveraging the capabilities of phytoremediation, this approach offers a promising pathway for mitigating the environmental and health impacts of mercury pollution in ASGM-affected areas while fostering sustainable development.

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