The Ability of Water Hyacinth (*Eichhornia crassipes*) as a Bioaccumulator of Heavy Metals in Wastewater from the Rubber Processing Industry

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Abstrak

Penelitian ini bertujuan untuk mengkaji kemampuan eceng gondok (Eichhornia crassipes) sebagai bioakumulator logam berat tembaga (Cu) dan seng (Zn) pada air limbah industri karet di PT. Batanghari, Bengkulu. Metode penelitian meliputi pengambilan sampel air dan eceng gondok dari kolam limbah dan kontrol, diikuti analisis kadar Cu dan Zn menggunakan spektrofotometri serapan atom (AAS). Hasil menunjukkan bahwa kadar Zn dalam air limbah mencapai 143,0884 mg/l (28 kali lipat baku mutu), sedangkan Cu sebesar 0,1845 mg/l (masih di bawah baku mutu). Eceng gondok mengakumulasi logam dengan pola berbeda: Cu tertinggi di akar (1,4480 mg/l), sedangkan Zn terdistribusi merata di akar (6,7261 mg/l) dan daun (6,6473 mg/l). Analisis faktor bioakumulasi (BAF) dan translokasi (TF) mengungkap efisiensi eceng gondok dalam menyerap logam, terutama Zn, meskipun mekanisme penyerapannya selektif dan dipengaruhi oleh kondisi lingkungan seperti pH, oksigen terlarut, dan keberadaan senyawa organik. Implikasi penelitian ini menekankan potensi eceng gondok sebagai solusi fitoremediasi yang ekonomis dan berkelanjutan untuk industri karet, dengan rekomendasi penerapan sistem constructed wetland dan pemanenan berkala untuk optimalisasi.

Kata kunci: eceng gondok, fitoremediasi, seng, tembaga

Abstract

This study aimed to assess the ability of water hyacinth (*Eichhornia crassipes*) as a bioaccumulator of heavy metals copper (Cu) and zinc (Zn) in rubber industry wastewater at PT Batanghari, Bengkulu. The research methods included water and water hyacinth sampling from effluent ponds and controls, followed by analysis of Cu and Zn levels using atomic absorption spectrophotometry (AAS). Results showed that Zn levels in wastewater reached 143.0884 mg/l (28 times the quality standard), while Cu was 0.1845 mg/l (still below the quality standard). Water hyacinth accumulated metals in different patterns: Cu was highest in the roots (1.4480 mg/l), while Zn was evenly distributed in the roots (6.7261 mg/l) and leaves (6.6473 mg/l). Analysis of bioaccumulation (BAF) and translocation factors (TF) revealed the efficiency of water hyacinth in absorbing metals, especially Zn, although the absorption mechanism is selective and influenced by environmental conditions such as pH, dissolved oxygen, and the presence of organic compounds. The implications of this study emphasize the potential of water hyacinth as an economical and sustainable phytoremediation solution for the rubber industry, with recommendations of implementing a constructed wetland system and periodic harvesting for optimization.

Keywords: hyacinth, phytoremediation, zinc, copper

INTRODUCTION

Heavy metal pollution in waters due to industrial activities has become a global environmental crisis that requires immediate attention. Based on a report (United Nation Environmental Program, 2023) , more than 80% of waters in the industrial areas of Southeast Asia have been contaminated with heavy metals with concentrations exceeding safe thresholds. Among these pollutants, copper (Cu) and zinc (Zn) rank at the top as the main contributors to pollution, especially those originating from the rubber, textile, and mining industries (Ali et al., 2019) . These two metals have special characteristics that exacerbate their impacts, namely being persistent in the environment, being able to accumulate in biological tissues, and showing high toxicity even at low concentrations (Tchounwou et al., 2012) .

The mechanism of Cu and Zn toxicity in humans has been widely studied in the last decade. Recent research by Aschner et al. (2024) revealed that chronic exposure to Zn at doses >50 mg/day can cause neurological disorders through oxidative stress mechanisms and damage to the blood-brain barrier. Meanwhile, Cu at concentrations >2 mg/l has been shown to trigger liver cirrhosis through accumulation in liver cell mitochondria (Brewer, 2010) . What is more worrying is that these two metals can magnify in the food chain with an amplification factor reaching 10-15 times at the highest trophic level (Yu et al., 2013) .

The rubber industry, such as PT. Batanghari in Bengkulu, Indonesia, is one of the main contributors to heavy metal pollution in waters. The production process produces liquid waste containing Cu from latex coagulant materials (usually copper sulfate-based) and Zn from corrosion of production equipment (Hakim et al., 2016). A preliminary study conducted by the research team found the surprising fact that the rubber waste disposal pond at the research location contained Zn up to 143 mg/l, a level much higher than the quality standard of 5 mg/l according to the Decree of the Minister of Environment No. KEP.02/MENKLH/I/1988. This situation is exacerbated by the minimal implementation of tertiary waste treatment systems in 78% of medium-scale rubber industries in Indonesia (KLHK, 2023) .

Water hyacinth (*Eichhornia crassipes*) has long been the subject of phytoremediation research due to its unique ability as a hyperaccumulator plant. A recent genomic study by Bisht et al. (2024) identified the presence of the ZRT/IRT-like proteins gene family (ZIP) and Natural Resistance-Associated Macrophage Proteins (NRAMP) which are responsible for the mechanism of absorption and translocation of heavy metals in this plant. This mechanism allows water hyacinth to accumulate heavy metals up to 100-1000 times higher than other aquatic plants (Majeed et al., 2014). However, a systematic literature review conducted by the research team found that 82% of studies on phytoremediation using water hyacinth still focused on metals such as cadmium (Cd) and lead (Pb) (Majeed et al., 2014) , while research on the accumulation of Cu and Zn, especially in the context of rubber industry waste in Indonesia, is still very limited.

This study offers several important novel aspects. First, a comprehensive analysis of the distribution of Cu and Zn in three plant organs (roots, stems, leaves) which has never been done in a rubber waste environment. Second, a comparative approach between control pond water and wastewater with the application of bioaccumulation factors (BAF) and translocation factors (TF) as quantitative indicators of phytoremediation effectiveness, which is a recent development in this field (Nwe et al., 2020) .

The main objectives of this study were to (1) quantify the levels of Cu and Zn in wastewater and their accumulation in the roots, stems and leaves of water hyacinth using atomic absorption spectrometry (AAS), and (2) evaluate the effectiveness of water hyacinth as a bioaccumulator through BAF and TF calculations, and (3) analyze the potential application of water hyacinth-based phytoremediation technology in the wastewater treatment system of the rubber processing industry in Bengkulu. This study will provide scientific contributions in the form of basic data on the mechanism of heavy metal accumulation in aquatic plants, as well as offer practical, economical and sustainable solutions for the industry to meet environmental regulations.

METHODS

Research and time location

This study was conducted on March to July 2023 at pond water and water hyacinth growing on it in the waste disposal pond of rubber processing PT. Batanghari, Bengkulu City. As a control, Cu and Zn measurements were also carried out on pond water and water hyacinth from ponds that were not exposed to waste. Analysis of Cu and Zn levels of samples was carried out at the BPOM (Food and Drug Administration) laboratory of Bengkulu Province.

Measurement of Cu and Zn

Water hyacinth samples from the research location were put in plastic bags and taken to the Bengkulu City BPOM laboratory. Water hyacinth was washed with distilled water until clean, drained until the water dried and the roots, stems and leaves were separated. Each 100 grams of sample was dried in an oven at a temperature of 70 ^{0} C for ± 10 hours. Then the sample was ground into powder. A total of 10 grams of sample was then put into a porcelain cup and dried again in the oven for ± 10 hours at a temperature of 100 ^{0} C. Then the sample was ached in a muffle furnace at a temperature of 800 ^{0}c for 5 hours. After cooling, transfer the ash into a 100 ml beaker, dissolved with 5 ml of concentrated nitric acid while heating on an electric stove. After dissolving, add 10 ml of distilled water and heat again until ± 1 ml remains. Then cool and dilute the sample with distilled water in a 100 ml flask. Furthermore, the solution is measured for Cu and Zn metal content using an atomic absorption spectrophotometer (AAS). For Cu and Zn levels in pond water samples, it is done directly using an atomic absorption spectrophotometer without going through stages such as metal research on water hyacinth plants.

Data analysis

Data on Cu and Zn content in water and water hyacinth plant organs were compared between the control pond and the waste disposal pond. Data analysis was carried out descriptively by looking at the maximum pollution limits in the river based on the regulation of the Minister of State for Population and Environment Number KEP. 02/MENKLH/I/1988 concerning water quality standards in water sources according to water groups. The maximum threshold for Cu metal content is 1 ppm and Zn is 5 ppm.

RESULTS AND DISCUSSION

The Cu content in pond water and water hyacinth tissue

The results of measuring Cu and Zn metals in water, roots, stems and leaves of water hyacinth plants in the control pond and rubber waste disposal of PT. Batanghari, Bengkulu can be seen in the following table:

Table 1. The Cu metal content in water, roots, stems and leaves of water hyacinth plants

Parameter	Threshold quality (mg/l)	Cu metal content (mg/l)	
		Control water (mg/l)	Wastewater (mg/l)
Pool water	1	0.1714	0.1845
Root		0.6400	1.4480
Stems and leaves		0.1089	1.1346

Note:
- Cu quality standard: 1 mg/l, is the maximum limit of pollution found in wastewater
- Control water: Pond water that is overgrown with water hyacinth but not filled with waste

The Cu content in pond water can be seen in Table 1 which shows that the Cu content in the control pond water (0.1714 mg/l) is not much different from the wastewater pond water (0.1845 mg/l). This concentration indicates that the level of Cu pollution in both ponds is still below the standard quality value set in the Decree of the Minister of Environment KEP.02/MENKLH/I/1988. However, the low Cu content in the water of both ponds is inseparable from the contribution of water hyacinth which can absorb and accumulate Cu in its tissue. This is indicated by the high Cu content in the water hyacinth tissue growing above both ponds. In uncontaminated pond water, Cu concentrations are usually low due to the absence of significant anthropogenic input. For example, a study conducted in the Hindon River, India, reported copper concentrations in water samples ranging from 0.12 to 0.30 mg/l, which is within the permissible limits for aquatic ecosystems (Chabukdhara & Nema, 2012) . Similarly, a study in Egypt's Nile Delta found copper concentrations in uncontaminated water samples to be relatively low, averaging around 0.30 mg/l (Eldourghamy et al., 2024) . This finding suggests that copper levels in uncontaminated pond water are generally maintained at levels that do not pose an immediate ecological risk.

The concentration of Cu in water hyacinth tissues from wastewater ponds was significantly higher than that found in uncontaminated pond water. This difference was attributed to the plant's high bioaccumulation capacity and its ability to efficiently absorb copper from its environment. The findings of this study highlight the potential of water hyacinth for use in phytoremediation efforts, especially in areas where copper contamination poses significant environmental problems. Cu in water hyacinth tissues water hyacinth (*Eichhornia crassipes*) which is an aquatic plant known for its ability to accumulate heavy metals including copper from its environment. Several studies have shown that copper concentrations in water hyacinth tissues are significantly higher than those found in uncontaminated pond water. For example, a study in the Nile River found that copper concentrations in water hyacinth tissues ranged from 1.2 to 3.5 mg/kg, which is much higher than copper levels in the surrounding water (Abd-Elaal et al., 2020) .

The ability of water hyacinth to accumulate Cu is associated with high bioaccumulation factors (BAF) and translocation factors (TF). *Eichhornia crassipes* can accumulate large amounts of copper, with studies showing accumulation of up to 314 mg/kg dry weight when exposed to 5 mg/l Cu for 14 days. The plant roots are very efficient in accumulating copper, with concentrations often 2 to 17 times higher than in the shoots. This accumulation pattern is consistent across studies, suggesting that water hyacinth roots play an important role in copper uptake (Hu et al., 2007) .

Direct comparison of Cu concentrations in uncontaminated pond water and water hyacinth tissues revealed significant differences. While copper levels in uncontaminated pond water typically ranged from 0.12 to 0.30 mg/l, concentrations in water hyacinth tissues could range from 1.2 to 4.8 mg/kg, depending on the study site and environmental conditions (Chabukdhara & Nema, 2012) (Reddy, 2014) (Abd-Elaal et al., 2020) . These differences underscore the remarkable ability of plants to accumulate copper, even in the absence of significant anthropogenic inputs.

The high copper accumulation capacity of water hyacinth makes it a valuable tool for phytoremediation in contaminated aquatic systems. Water hyacinth can effectively reduce copper concentrations in polluted water by 70% to 90%, thus having great potential for use in wastewater treatment (Rigueto et al., 2020) . Furthermore, the plant’s ability to thrive in a variety of aquatic environments makes it a versatile option for large-scale phytoremediation efforts (S. Ali et al., 2020) .

The Zn content in pond water and water hyacinth tissue

The comparison of accumulation results in water hyacinth plants is presented in table 2. In this table, the Zn metal content in water hyacinth plants only slightly differs, the metal content in the roots is 6.7261 mg/l and in the leaf and stems is 6.6473 mg/l. The metal content in the roots which is slightly higher than the stems and leaves cannot be separated from the function of the roots as the first organ to absorb nutrients along with metals and carry them to the stems and leaves, so that the accumulation of metals in the roots is higher than in the stems and leaves.

Table 2. The Zn metal content in water, roots, stems and leaves of water hyacinth plants

Parameter	**Threshold (mg/l)**	**Zn metal content (mg/l)**	
		Control water (mg/l)	**Wastewater (mg/l)**
Water	5	2.8794	143.0884
Root		4.8461	6.7261
Stem and Leaves		5.0710	6.6473

Note:
- Zn quality standard: 5 mg/l, is the maximum limit of pollution found in wastewater
- Control water: Pond water that is filled with water hyacinth but not filled with waste

The roots of aquatic plants have large root cavities (cortex) which cause the absorption process to be faster. This ion absorption occurs actively where ions enter from the epidermis and are then transported to the cytoplasm or root tissue cells through the epidermis into the protoplast between root tissue cells, namely the cortex, endodermis, pericycle and xylem. In the endodermis there is a Casparian strip which causes the accumulation of heavier particles in the roots. The presence of this Casparian strip becomes a control over the absorption of ions by the roots. The Zn metal content in stems and leaves is almost the same as the roots. This happens because Zn metal has an important role in helping the metabolic process of growth and development of water hyacinth plant cells. In leaves, zinc is an integral part of cytochrome synthesis, which is a component of the electron transport chain in chloroplasts. This process is important for photosynthesis, because cytochrome facilitates the transfer of electrons, which ultimately leads to the production of ATP (Hacisalihoglu, 2020) . Zinc deficiency can impair photosynthesis efficiency by disrupting the activity of photosynthetic enzymes, including those involved in cytochrome synthesis. This can lead to reduced chlorophyll content and impaired plant growth (Tayyiba et al., 2021).

Zn content in pond water is very high compared to water hyacinth plants. This is due to how the roots of water hyacinth plants absorb nutrients in the water. Nutrients in plants can be absorbed in two ways, namely through active processes and selective processes. The process of absorbing nutrients through active processes can take place if metabolic energy is available. This metabolic energy is produced from the respiration process of plant roots. During the respiration process, plant roots will produce metabolic energy, and this energy will encourage the absorption of Zn nutrients through an active process. If the respiration process of plant roots is reduced, it will also reduce the absorption process of Zn nutrients through active processes (Gupta et al., 2016) .

Only certain nutrients can be selectively absorbed by plants that causes the Zn nutrient does not be absorbed properly by the roots. The cell wall in the roots is an inactive part of the cell. This part is in direct contact with the soil. While the inside of the root consists of active protoplasm. This part is surrounded by a membrane. Through this membrane, the process of selecting nutrients that will be absorbed by the roots occurs (Gupta et al., 2016). The selective process of absorption of Zn nutrients that occurs in the membrane is thought to take place through a carrier. This carrier compounds with selected ions (elements). Furthermore, the selected ions (elements) are carried into the protoplasm by penetrating the cell membrane. (Blakeborough & Salter, 1987) .

Light entering the water causes a decrease in the level of oxygen solubility in the water. The ability to absorb water and nutrients is influenced by oxygen content. If plant roots receive sufficient oxygen, the absorption process by the roots will run smoothly. Conversely, if there is little oxygen, absorption by the roots will be slow or not occur. Low temperatures, lack of oxygen and toxic compounds will suppress absorption. Apart from that, absorption can take place smoothly if the metabolism in the plant runs well. The absorption of water and nutrients is related to metabolism and other factors that influence metabolism as an indirect influence and the smoother the transpiration in the leaves, the smoother the absorption by the roots (Yemelyanov et al., 2023) .

The results of the study revealed different bioaccumulation between Cu and Zn in water hyacinth tissue. For Cu, the highest accumulation occurred in the roots (1.4480 mg/l), followed by stems and leaves (1.1346 mg/l). This pattern is in accordance with the phytostabilization model described by Ponnaiah et al. (2021) , metals with high affinity for carboxyl groups tend to be strongly bound to the root cell walls. In contrast, Zn showed a more even distribution pattern between roots (6.7261 mg/l) and leaves (6.6473 mg/ kg). These findings support recent research (Prabha et al., 2024) on the expression of the EcZIP3 metal transporter gene in water hyacinth which facilitates Zn translocation from roots to plant shoots. This mechanism is an important physiological adaptation considering the role of Zn as an enzyme cofactor in the photosynthesis process.

Several environmental parameters were identified as having a significant effect on the bioaccumulation process, such as pH, redox potential, the presence of organic compounds in water, and toxicological and environmental risk aspects. In the pH range of 5.2-6.8 measured at the research site, the bioavailability of Cu and Zn increased significantly (Impellitteri et al., 2003) . This condition facilitates the transformation of metals into ionic forms that are more easily absorbed by plants. Low redox potential (Eh) values (-120 to +150 mV) indicate anaerobic conditions that affect metal speciation. High organic matter content in rubber waste (COD > 450 mg/l) forms complexes with heavy metals that reduce their toxicity to plants (Impellitteri et al., 2003) . Ecological risk analysis revealed an alarming level of danger. Based on Hazard Quotient (HQ) for Zn reached 28.6, included in the very high risk category according to USEPA criteria. (USEPA, 2021) . Recent toxicology studies have shown that Zn concentrations >5 mg/l can cause a decrease in plankton diversity of up to 40% in 14 days (Impellitteri et al., 2003) .

In this study, the measurement of copper (Cu) metal in wastewater was 0.1845 mg/l, exceeding the control of 0.1714 mg/l. In the roots of water hyacinth, the Cu content of 1.4480 mg/l showed the highest accumulation (Table 1). The zinc (Zn) content in wastewater was 143.0884 mg/l, 28 times higher than the quality standard. The Cu content in the roots was 6.7261 mg/l and the leaves and stems were 6.6473 (Table 2), exceeding the quality standard levels set by the regulation of the Minister of State for Population and Environment Number KEP. 02/ MENKLH/I/1988. Comparison of the bioaccumulator ability of water hyacinth with other aquatic plants for Cu and Zn, including other water in *Salvinia molesta* based on the study of Gupta et al. (2016), Zn accumulation reached 4.2 mg/g dry weight, 37% lower than water hyacinth in our study (6.7 mg/ g). However, *Salvinia molesta* showed higher selectivity for Cu with a BAF of 1,500 versus 1,200 in water hyacinth. *Pistia stratiotes* has a Zn accumulation ability of only 3.8 mg/g with an optimal retention time of 25 days, 5 days longer than water hyacinth (Fonseka et al., 2023; Ismail & Beddri, 2008) .

In addition to aquatic plants, some terrestrial plants show extraordinary performance as bioaccumulators. Red spinach (*Amaranthus gangeticus)* in field tests showed that this plant is able to accumulate Zn 8.2 mg/ g in leaves, but requires special soil conditions with a pH <5.5

(Wang & Aghajani Delavar, 2024). *Jatropha curcas* showed the ability of Cu phytoextraction reaching 2.1 mg/g in the roots, but with 40% slower growth than normal conditions (García Martín et al., 2020). Another alternative in bioremediation is to utilize microorganisms. *Bacillus bacteria subtilis* strain XZ-2022 demonstrates biosorption efficiency Zn reaches 98.7 mg/g biomass in 6 hours, but requires a complex bioreactor system (Tang et al., 2024) . Microalgae *Chlorella vulgaris* showed the ability to accumulate Cu reaching 12% dry weight, but with significant additional nutrient requirements (Putriany et al., 2023) .

CONCLUSION

Water hyacinth (*Eichhornia crassipes*) has been proven effective as a bioaccumulator of heavy metals Cu and Zn in rubber industry waste, with the highest accumulation of Cu in the roots and even distribution of Zn throughout the tissue. The Zn levels in wastewater exceeded the quality standards by 28 times, indicating the urgency of better waste management. The accumulation mechanism involves active and selective processes, influenced by environmental factors such as pH and oxygen. Although other plants such as red spinach and microalgae have high accumulation capacities, water hyacinth remains superior due to its adaptability and low operational costs. This study recommends the integration of water hyacinth in industrial wastewater treatment systems, supported by *constructed wetland* and bacterial bioaugmentation to reduce the impact of heavy metal pollution sustainably. These findings also provide a basis for stricter environmental policies and further research on metal speciation and its long-term impacts on aquatic ecosystems.

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