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Efficiency of Water Hyacinth (Eichhornia crassipes) in the Phytoremediation of Copper-Contaminated Waters of Lake Tempe, South Sulawesi Indonesia

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ABSTRACT

Lake Tempe, situated in Wajo Regency, South Sulawesi, Indonesia, is currently experiencing increased levels of toxicity due to heavy metal contamination stemming from industrial operations and human activities in the area. The presence of copper (Cu), a heavy metal, in water has been reported to raise concerns regarding the potential negative effects on the local ecosystem. This indicates that there is a need to develop a phytoremediation technique to efficiently reduce the levels of contamination. Therefore, this study aimed to assess the effectiveness of water hyacinth phytoremediation in reducing Cu contamination. Metal-contaminated water medium from Lake Tempe was used to cultivate water hyacinth, and the 30-day trial was carried out in a natural setting. Control was carried out as a comparison by measuring the decrease in Cu levels in the water. Measurements of the physicochemical characteristics of water were carried out both before and after phytoremediation process. The results showed that the levels of pH, total suspended solid (TSS), dissolved oxygen (DO), and Cu decreased after the procedure. Furthermore, there was an increase in the values of BOD5, total dissolved solid (TDS), total nitrogen content, and total phosphate (P). Water hyacinth capacity to absorb metals was determined by measuring the bio-concentration factor (BCF). The results showed a decrease in Cu levels with a range of 7.1692 mg/kg to 14.0202 mg/kg for 30 days. The BCF value obtained was 94.2217, indicating that there is a relationship between the BCF value and the phytoremediation time. The higher the value obtained, the longer the phytoremediation. The infrared data indicated that Cu was attached to the test plant by engaging the C=S, C=N, and O-H functional groups. Based on the results, water hyacinth could be used as a phytoremediation agent to reduce the levels of Cu in water.

1. INTRODUCTION

Tempe Lake is located in Wajo Regency, South Sulawesi and covers an area of around 13,000 Ha. The local community uses it as water transportation, a place to wash clothes and even as a place to dispose of textile waste. Water contamination in Lake Tempe has raised significant concern, primarily due to the indiscriminate discharge of liquid waste from various industrial sources. This condition has led to the accumulation of heavy metal, which are detrimental to both human health and aquatic ecosystems. Furthermore, to address this problem, several studies have been conducted on the use of phytoremediation to decrease heavy metal accumulation [1].

Phytoremediation is a technology that uses plants as agents to reduce soil and water contamination. This technique is also cost-effective and durable in the remediation of contaminated sites. Phytoremediation method is primarily conducted through the use of a specific aquatic plant, known as water hyacinth (Eichhornia crassipes). The use of the plant as a phytoremediator in heavy metal-contaminated waters has gained worldwide recognition. Water hyacinth as a phytoremediation agent absorbs metals in contaminated water, forming large amounts of phytochelatin metal complexes which are then detoxified [2-4]. The formation of phytochelatin, water hyacinth will accumulate heavy metals in certain areas of its cells, without interfering with metabolic processes. However, it is important to note that the presence of excessive water hyacinth can disrupt the aquatic ecosystem due to the ability to reduce the solubility of oxygen. Several studies showed that it had a rapid growth rate, allowing the plant to proliferate quickly and cover the entire water surface [5, 6].

To ensure the optimal absorption of heavy metal during phytoremediation process, it is crucial to control the growth of water hyacinth. The plant shows a significant biomass production level and possesses excellent heavy metal absorption capacity, making it well-suited for wastewater treatment. Water hyacinth has a high carbon content with 60% cellulose, 8% hemicellulose, and 17% lignin, which contributes to its adsorption ability [7]. Furthermore, it belongs to the Pontedariaceae Family and thrives in shallow ponds, washes, wetlands, slow aqueducts, lakes, budgets, and gutters. The cellulose content in activated carbon derived from water hyacinth plays an essential role in binding heavy metal in water. According to the World Health Organization (WHO) (1984), the metal of greatest concern in water contamination is cadmium, chromium, copper (Cu), lead, nickel, and zinc. Although Cu is an essential micronutrient for plant, it can become toxic at high concentration [5, 8].

Cu is a naturally occurring element that is often found in the Earth crust and classified as a heavy metal. In the natural environment, its concentration typically ranges from 0.2-30 µg/L in fresh water. More than this value, waters are considered polluted and require countermeasures. Cu pollution in lake water has a serious impact on the environment and the living organisms in it. Some of the impacts include toxicity to organisms, disruption of the ecosystem system, accumulation in organisms, pollution of drinking water. Therefore, it is important to control and prevent copper pollution in lake water through wise waste treatment practices, regular monitoring of lake water quality to identify potential problems early and countermeasures with safe techniques. Therefore, this study aims to assess the effectiveness of phytoremediation using water hyacinth in reducing Cu content in Lake Tempe.

2. MATERIALS AND METHODS

2.1 Sampling of water and water hyacinth (*E. crassipes*) in Lake Tempe

The research was carried out using water hyacinth plants which function as phytoremediation plants. This plant is used to remediate metals in polluted Tempe Lake water. Plants were placed in a square basin with Tempe Lake water without adding nutrient media for 1 week to allow the plants to adapt to the new environment, and then plants of the same size were selected for phytoremediation experiments. Water samples were obtained from the waters of Lake Tempe located in South Sulawesi, Indonesia [9].

2.2 Acclimatization process for water hyacinth (*E. crassipes*)

This acclimatization process is carried out for 7 days without any additional nutrition. After the acclimatization process was complete, good quality samples of water hyacinth (*E. crassipes*) were selected and a square container, namely 20 cm high and 20 cm long, was used in the phytoremediation experiment. Meanwhile, the Tempe Lake water samples obtained were added by adding $CuCl_2$ with a concentration of 50 ppm. In this study, it was conditioned by temperature, humidity and sunlight to maintain optimal environmental conditions for plants during the acclimatization and phytoremediation processes [10].

2.3 Analyzing Lake Tempe water sample physicochemical

The total nitrogen, total phosphate (P), pH test, total dissolved solid (TDS) test, total suspended solid (TSS), Dissolved Oxygen (DO), and Chemical Oxygen Demand (COD) test were all part of the physicochemical analysis. Analyses were carried out before and after phytoremediation process. Initial values were those recorded at zero (0) days, while the final values were reported after phytoremediation [10].

2.4 Examination of copper levels in Lake Tempe water and water hyacinth (*E. crassipes*)

Water hyacinth exposed to Cu(II) 50 ppm in the contaminated water were subjected to the 30-day phytoremediation after coming into contact with water. Atomic Absorption Spectrophotometer (AAS) was used to measure the amount of zinc in the sample 4 times at 10-day intervals [11].

2.5 Bio-concentration factor (BCF)

BCF score showed the amount of heavy metal that could be absorbed by plant in a contaminated area. According to BCF, the metal concentration in plant was directly correlated with the metal concentration in water [12].

2.6 Analysis of infrared (IR)

Water hyacinth compounds' functional groups were identified using IR spectroscopy. To create pellets with KBr, the dry powder of water hyacinth was weighed to a maximum of ± 1 mg. IR spectroscopy was then used to examine the dried pellets [13-15].

3. RESULTS AND DISCUSSION

3.1 Examining Lake Tempe physicochemical characteristics

The physical and chemical characteristics of Lake Tempe water that had been contaminated with Cu were examined both before and after the 30-day phytoremediation. The parameters identified include pH, TDS, TSS, total N and total P. Table 1 presents water phytochemical analysis.

Physicochemical analysis of water and Cu was conducted using multiple criteria before and after phytoremediation in water hyacinth experiment described in Table 1, with pH of 7.22 and 7.37. TSS varied between 68 and 32 mg/L before the application of phytoremediation, but TDS increased from 164 to 265 mg/L. Nitrogen content increased from 1.9670 mg/L to 3.7659 mg/L after phytoremediation, while Chemical Oxygen Demand (COD) increased from 17.2047 mg/L to 160.136 mg/L, and dissolved oxygen (DO) from 6.1722 mg/L to 4.4557 mg/L, according to an examination of total nitrogen. In terms of total P, Cu decreased from 0.8838 mg/L to 0.1488 mg/L and P from 0.0458 mg/L to 1.2495 mg/L.

The concentration of hydrogen ions (H+) in a solution was measured to estimate the pH or acidity levels. Table 1 shows the pH analysis results for sample of water contaminated with Cu before and after the 30-day phytoremediation. After 30 days, the pH values decreased, suggesting that the treatment was generally acidic. Sunlight was one of the environmental elements that could induce the condition. This could also occur due to the falling off of plant parts and alteration of the pH levels as well as the oxidation process that formed sulfate [16]. Another factor influencing the decline was the activity of plant in absorbing heavy metal.

Table 1. Physicochemical characteristics of Cu-contaminated Lake Tempe water in phytoremediation studies using water hyacinth

Parameters	Before	After	Unit	Test Method
pH	7.37	7.22	-	SNI 06-6989.11-2004
TDS	164	265	mg/L	SNI 06-6989.27-2005
TSS	68	32	mg/L	SNI 06-6989.3-2004
Total N	1.9670	3.7659	mg/L	AOAC Official Method 973.48.18th Ed, 2005
COD	17.2047	160.136	mg/L	SNI 6989.2:2009
DO	6.1722	4.4557	mg/L	SNI 06-6989.14-2004
Total Phosphate as P	0.0458	1.2495	mg/L	SNI 06-6989.31-2005
Cu	0.8838	0.1488	mg/L	SNI 06-6989.8-2004

TDS was the measurement of solid smaller than suspended solid. Although an excessive TDS could raise the turbidity of natural water, further prevent sunlight from penetrating water, and impact photosynthesis, TDS in natural water was not harmful [17]. The results showed that after phytoremediation, there was an increase in TDS levels in water. Due to the extended phytoremediation duration, a huge number of water hyacinth parts died, leading to an increase and deposition of various organic chemicals in the planting media. The degree of water turbidity and the increase in TDS were also directly correlated. This indicated that the higher the TDS concentration, the higher the levels of turbidity, and vice versa. The maximum total of adsorbed dissolved solids was then reached. This was due to a coating of adsorbed Cu covering the surface of the aquatic plant biosorbent, water hyacinth. The release of monovalent or divalent ions, such as Na, Ca, and Mg, which were present in plant cell walls and exchanged for heavy metal through ion exchange reactions, could lead to an increase in TDS readings [17].

TSS was the measurement of suspended solid in waste that had a size of less than 0.45 microns [17]. TSS test results showed that after phytoremediation, TSS value in water decreased. Several factors contributed to the reduction in TSS values after phytoremediation. The capacity of water hyacinth to remove suspended particles from water was one of the potential explanations for the decrease in TSS during phytoremediation. It had been shown that water hyacinth was useful in lowering TSS in wastewater. The process through which organic matter was broken down and transformed into nutrients for plant by microbes living in the roots of plant. The length of time the plant material was in contact with water. Greater TSS reduction could be caused by longer contact times between water and the plant material [18]. Phytoremediation was a promising process that showed potential for lowering TSS in wastewater and other kinds of water bodies. It was an economical and ecologically sustainable method that could be applied to enhance water quality and safeguard aquatic environments.

The total N and P content of water was also examined in this study. The N and P concentration was one of the factors that could be examined to evaluate whether water was contaminated. Apart from the continuous processes of photosynthesis and decomposition, the plant was also subjected to a process of lowering the concentrations of these nutrients [19]. After phytoremediation, measurements of the total N and P content in water showed an increase. This was caused by fragments of fine roots, stems, or leaves falling into the planting medium and starting to decay.

Tests were also carried out including DO and COD values. These two parameters are important characteristics for understanding water conditions and the level of pollution. COD was a value that showed the amount of oxygen needed to oxidize organic compounds contained in 1 L solution expressed in mg/L units [20]. Organic compounds in COD included biodegradable and non-biodegradable components [21]. COD content in contaminated water increased after 30-day phytoremediation. This was caused by the large number of plant parts that died due to the extended process.

DO was a necessary component of all living organisms for respiration, metabolism, and the exchange of materials that yielded energy for development and reproduction. Due to the engagement of DO in the oxidation and reduction processes of both organic and inorganic components, oxygen was a significant indication of water quality. Furthermore, the levels influenced the biological activities performed by anaerobic or aerobic organisms. In an aerobic environment, it often oxidized both organic and inorganic elements, producing nutrients that could increase the fertility of water. In the form of nutrients and gases, oxygen generated under anaerobic conditions broke down chemical molecules into simpler variants. DO played a crucial role in reducing the contamination load on natural water and in aerobic treatment, which cleaned domestic and industrial wastewater due to the oxidation and reduction process [22]. Table 2 shows that water experienced a decrease in dissolved oxygen concentration after 30 days of phytoremediation. This decrease was caused by the deposition of several organic compounds in the planting medium, due to the large number of plant parts dying as the process progressed. The results of Cu concentration analysis in contaminated water showed a decrease in the metal's levels, indicating the ability of water hyacinth to reduce Cu in water.

Table 2. Cu levels in water hyacinth and Lake Tempe water

Time (Days)	Levels of Cu in Plant (mg/kg)	Levels of Cu in Water (mg/L)	BCF
0	<0.50	0.8838	0.5657
10	8.8376	0.0844	104.7109
20	7.1692	0.2173	32.9921
30	14.0202	0.1488	94.2217

Cu content absorbed by water hyacinth was measured for 30 days using AAS method, as shown in Table 2. In the initial examination, the results showed that Cu content in plant was <0.50 mg/kg and water had 0.8838 mg /kg with a BCF of 0.5657. On the 10th day, Cu levels were found in plant and water to be 8.8376 mg/kg and 0.0844 mg/kg, respectively with a BCF of 104.7109. The levels found in plants and water on the 20th day were 7.1692 mg/kg and 0.2173 mg/kg, respectively, with a BCF of 32.9921. On day 30, Cu in plants and water was 14.0202 mg/kg and 0.1488 mg/kg, respectively, with BCF 94.2217.

BCF measurements showed the tendency of Cu to be absorbed by water hyacinth. This parameter is used in environmental science and toxicology to measure the ability of a chemical substance to accumulate in the tissue of living organisms with the relationship between the concentration of the substance in the surrounding water environment. Furthermore, BCF was obtained from a comparison between chemical concentrations in water and plant [23]. The BCF value is calculated based on dry weight of the plant. Plant with higher BCF values had a greater ability to absorb heavy metal. Table 2 showed that the value from the first day (day 0) to the 30th day increased along with the length of phytoremediation. This showed the ability of water hyacinth as an effective phytoremediation medium in absorbing metal.

Plant in the growth process consisted of roots as a medium for absorbing water and transpiration through the leaves. This absorption also allowed contaminants in the form of cations to be carried away. Roots had phytochelatin compounds, which functioned to bind metal, bringing it into cells through an active transport process. Plant then formed reductase enzymes in the membranes to reduce metal, which was translocated to other parts of the plant through the xylem and phloem transport network. Heavy metal (Cu) was bound by chelate molecules and accumulated in other plant parts, such as stems and leaves. Plant also carried out an inductive tolerance mechanism for heavy metals by synthesizing metal-binding polypeptides, namely phytochelatin.

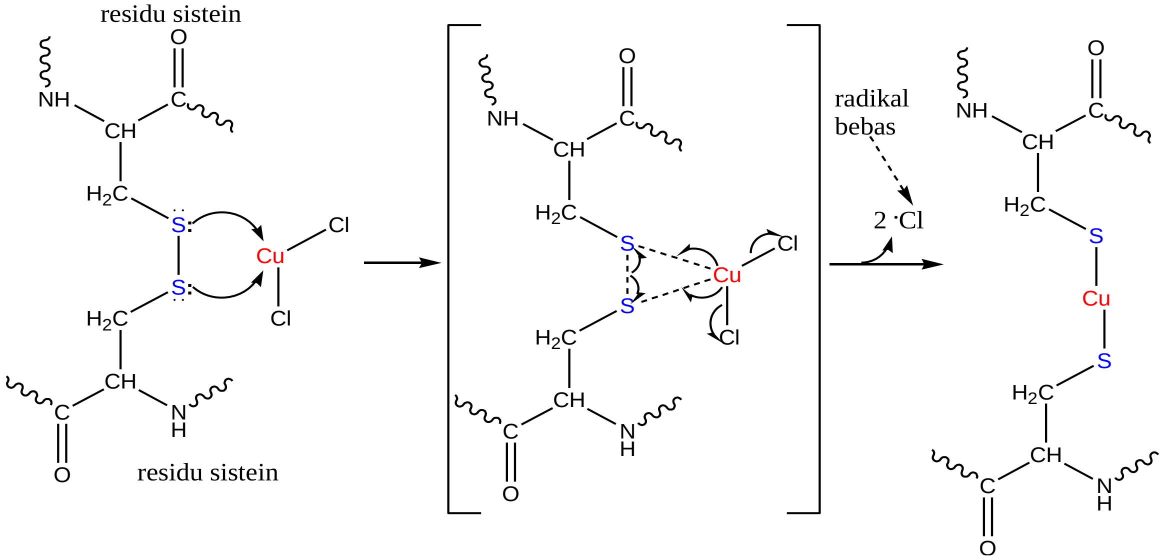

Figure 1. Reaction of cysteine (the constituent amino acids of phytochelatin) with the metal ion Cu(II)

Water hyacinth binds metals by forming phytochelatin. Figure 1 shows the phytochelatin reaction between water hyacinth and Cu(II) metal ions. Water hyacinth, in the mechanism of binding Cu, were first offered poison by chelating it with phytochelatins (small peptides with lots of cysteine amino acids containing sulfur). Sulfur atoms (S) had been reported to be very important for binding metal. The formation of phytochelatin was a plant response to adapt to vulnerable environmental conditions. Furthermore, the detoxification mechanism is by accumulating metals in certain organs. Through this mechanism, metals will be deposited in vacuoles so that they do not interfere with cell metabolic processes. Vacuoles are a safe place to accumulate metals because of their location [24].

Phytochelatin produced by plants can be triggered by Reactive Oxygen Species (ROS) [25]. ROS are reactive molecules that include a variety of chemical species. When plants experience oxidative stress caused by an environment contaminated with heavy metals, plants will produce ROS as a defense response. ROS production can cause oxidative damage to plant cells, but can also act as a signal that activates plant defense mechanisms, including phytochelatin synthesis. Phytochelatin is a peptide compound that helps in the detoxification of heavy metals by binding to them and forming a stable complex, thereby protecting plant cells from further damage caused by heavy metals. Thus, ROS can trigger phytochelatin synthesis as part of the plant's defense response to oxidative stress and heavy metal exposure.

Aside from binding to heavy metals, phytochelatins also play a vital role in transporting the metals to vacuoles for storage. This sequestration prevents the metals from interfering with essential cellular processes, which gives plants a crucial way to protect themselves against contamination by heavy metals [26]. In response to Reactive Oxygen Species, phytochelatin synthesis is induced. ROS stimulate other defense mechanisms as well as serve as a signal for phytochelatin production, highlighting the complex network of plant responses to oxidative stress and heavy metal exposure [27]. The complex and sophisticated process of phytochelatins in heavy metal detoxification not only reveals how plants adapt to difficult environmental conditions, but it also holds potential for biotechnological applications aimed at phytoremediation and enhanced stress tolerance in crops. Additional research in this field could uncover novel ways to reduce the effects of heavy metal pollution on plant ecosystems and human health [28].

Further research in this area could also lead to the development of novel approaches for reducing the harmful effects of heavy metal pollution on plant ecosystems and human health. This knowledge can pave the way for the development of sustainable solutions that address environmental issues and support global efforts to create ecosystems that are healthier and more resilient [29]. Phytochelatins highlight the adaptive nature of plants to environmental stress by inducing phytochelatin synthesis in response to Reactive Oxygen Species, as well as by binding heavy metals and transporting metals to vacuoles for storage, thereby preventing interference with critical cellular processes [30].

3.2 Identification of functional groups of water hyacinth

The biosorption process in water hyacinth of Cu could be identified using IR instrument. This instrument was able to detect interactions that occurred between Cu and water hyacinth through the spectrum produced before and after phytoremediation. Furthermore, plant contact with metal was carried out for 30 days.

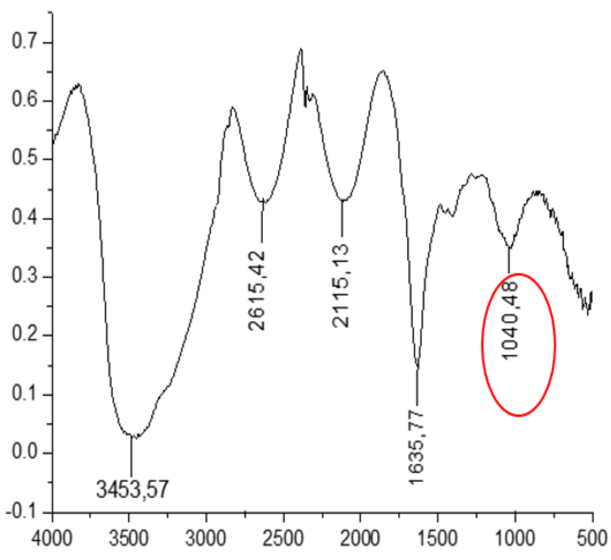

Figure 2. IR water hyacinth before phytoremediation

Figure 2 shows the IR data of water hyacinth before exposure to Cu and compared with Figure 3, the spectrum after exposure to Cu shows the wavelength changed in wave number (cm^{-1}). Furthermore, there was a typical absorption spectrum in the C=S group with a wavelength of 1040.48 cm^{-1} (before phytoremediation) to 1162.69 cm^{-1} (after phytoremediation). The wavelength shift of 122.21 cm^{-1} indicated that Cu was bound to the C=S functional group in water hyacinth. The IR data indicates that there is true chelation of Cu metal by water hyacinth. Furthermore, research can be carried out to compare the efficiency of phytoremediation of water hyacinth with other plants that have phytoremediation potential.

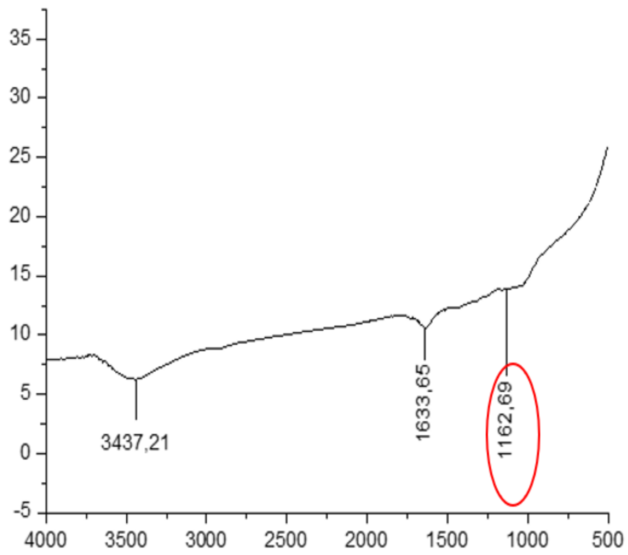

Figure 3. Water hyacinth IR after phytoremediation (Cu waste)

Identification via FTIR provides information on the presence of Cu in waste which is then absorbed by plants. It is hoped that this test will be more convincing that Cu can be accumulated in water hyacinth plants through the formation of complex phytochelatins. The results from the infrared data analysis of water hyacinth before and after exposure to Cu show strong evidence for the chelation of Cu metal by phytochelatins in water hyacinth, highlighting their role in metal detoxification and accumulation. These findings support the possibility of using water hyacinth to chelate Cu metal by phytochelatins.

4. CONCLUSIONS

In conclusion, water hyacinth could be used for Cu phytoremediation in Lake Tempe water. Water hyacinth has a fast growth rate in waters, so it is easier to use it to absorb metals in contaminated waters. Furthermore, it was discovered that Cu levels in water decreased by 7.1692 mg/kg to 14.0202 mg/kg over 30 days. Plants with higher BCF value have a greater ability to absorb heavy metals. Water hyacinth binds metals by forming phytochelatin through translocation and detoxification mechanisms. The sample IR data indicated that the C=S, C=N, and O-H functional groups were engaged in the attachment of Cu to water hyacinth.

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REFERENCES

[1] Le, H.Q., Chen, Y.C., Huynh, T.A., Thai, V.L. (2019). A study on removing arsenic contamination in soil by phytoremediation. Key Engineering Materials, 818: 113-117. https://doi.org/10.4028/www.scientific.net/KEM.818.113

[2] Levine, A.D., Tchobanoglous, G., Asano, T. (1991). Size distributions of particulate contaminants in wastewater and their impact on treatability. Water Research, 25(8): 911-922. https://doi.org/10.1016/0043-1354(91)90138-G

[3] Malik, A. (2007). Environmental challenge vis a vis opportunity: The case of water hyacinth. Environment International, 33(1): 122-138. https://doi.org/10.1016/j.envint.2006.08.004

[4] Nasir, M., Nur, M., Pandiangan, D., Mambu, S.M., Fauziah, S., Raya, I., Irfandi, R. (2022). Phytoremediation study of water hyacinth (Eichhornia crassipes) on Zinc metal ion (Zn^{2+}). International Journal of Design & Nature and Ecodynamics, 17(3): 417-422. https://doi.org/10.18280/ijdne.170312

[5] Nafisyah, E., Arrisujaya, D., Susanti, E. (2023). The utilization of water hyacinth (Eichhornia crassipes) harvested from the phytoremediation process as activated carbon in Cr (VI) adsorption. IOP Conference Series: Earth and Environmental Science, 1211(1): 012019.

[6] Nasir, M., Pandiangan, D., Mambu, S.M., Nur, M., Fauziah, S., Irfandi, R. (2023). Phytoremediation potential of water hyacinth (Eichhornia sp.), water spinach (Ipomea sp.), and apu wood (Pistia sp.) against metal ions Zn^{2+} in Tempe Lake, Wajo district, South Sulawesi. AIP Conference Proceedings, 2634(1).

[7] Ajibade, P.A., Andrew, F.P., Botha, N.L., Solomane, N. (2020). Synthesis, crystal structures and anticancer studies of morpholinyldithiocarbamato Cu (II) and Zn (II) complexes. Molecules, 25(16): 3584. https://doi.org/10.3390/molecules25163584

[8] Mokhtar, H., Morad, N., Fizri, F.F.A. (2011). Phytoaccumulation of copper from aqueous solutionsusing Eichhornia crassipes and Centella asiatica. International Journal of Environmental Science and Development, 2(3): 205.

[9] Rahim, S.W., Takhir, Q.A., Kudsiah, H., Rukminasari, N., Yanuarita, D. (2022). Water quality analysis in Tempe Lake Wajo Regency, South Sulawesi. IOP Conference Series: Earth and Environmental Science, 1119(1): 012090.

[10] Churko, E.E., Chitakira, M., Nhamo, L. (2023). Phytoremediation capacity of water hyacinth (Eichhornia crassipes) as nature-based solution for contaminants and physicochemical characterization of lake water. Water, 15: 2540. https://doi.org/10.20944/preprints202305.1051.v1

[11] Karam, F., Haddad, R., Amacha, N., Charanek, W., Harmand, J. (2022). Assessment of the impacts of phyto-remediation on water quality of the litani river by means of two wetland plants (Sparganium erectum and Phragmites australis). Water, 15(1): 4. https://doi.org/10.3390/w15010004

[12] Sulaiman, F.R., Hamzah, H.A. (2018). Heavy metals accumulation in suburban roadside plants of a tropical area (Jengka, Malaysia). Ecological Processes, 7(1): 1-11. https://doi.org/10.1186/s13717-018-0139-3

[13] Munene, J.M., Onyatta, J.O., Yusuf, A.O. (2020). Characterization of water hyacinth powder using FTIR spectroscopy and the adsorption behaviour of Pb^{2+}, Cd^{2+}, Zn^{2+}, Ni^{2+} and Cr^{2+} in Aqueous Solution. Asian Journal of Applied Chemistry Research, 6(1): 47-55. https://doi.org/10.9734/ajacr/2020/v6i130151

[14] Arivendan, A., Jebas Thangiah, W.J., Irulappasamy, S., N Chrish, B. (2022). Study on characterization of water hyacinth (Eichhornia crassipes) novel natural fiber as reinforcement with epoxy polymer matrix material for lightweight applications. Journal of Industrial Textiles, 51(5_suppl): 8157S-8174S. https://doi.org/10.1177/15280837211067281

[15] Mukaratirwa-Muchanyereyi, N., Kugara, J., Zaranyika, M.F. (2016). Surface composition and surface properties of water hyacinth (Eichhornia crassipes) root biomass: Effect of mineral acid and organic solvent treatment. African Journal of Biotechnology, 15(21): 891-896. https://doi.org/10.5897/AJB2015.15068

[16] Rahadian, R., Sutrisno, E., Sumiyati, S. (2017). Efisiensi penurunan cod dan tss dengan fitoremediasi menggunakan tanaman kayu apu (Pistia Stratiotes L.) studi kasus: Limbah laundry. Jurnal Teknik Lingkungan, 6(3): 1-8.

[17] Rohaningsih, D., Aisyah, S. (2023). Study of total dissolved solids (tds) and total suspended solids (tss) in estuaries in Banten Bay Indonesia. IOP Conference Series: Earth and Environmental Science, 1201(1): 012045. https://doi.org/10.1088/1755-1315/1201/1/012045

[18] Ruhmawati, T., Sukandar, D., Karmini, M., Roni S,T. (2017). Penurunan kadar total suspended solid (tss) air limbah pabrik tahu dengan metode fitoremediasi. Jurnal Permukiman, 12(1): 25-35.

[19] Su, F., Li, Z., Li, Y., Xu, L., Li, Y., Li, S., Wang, F. (2019). Removal of total nitrogen and phosphorus using single or combinations of aquatic plants. International Journal of Environmental Research and Public Health, 16(23): 4663. https://doi.org/10.3390/ijerph16234663

[20] Ramayanti, D., Amna, U. (2019). Analisis parameter COD (Chemical Oxygen Demand) dan pH (potential Hydrogen) limbah cair di PT. Pupuk Iskandar Muda (PT. PIM) Lhokseumawe. QUIMICA: Jurnal Kimia Sains dan Terapan, 1(1): 16-21.

[21] Umacina, M., Liestianty, D., Muliadi. (2014). Studi fitoremediasi tanah tercemar logam berat tembaga menggunakan tanaman kedelai (Glycine max (L) merill) dengan penambahan arang (Charcoal). Skripsi Univ. Khairun.

[22] Qin, L., Wang, D., Zhang, Z., Li, X., Chai, G., Lin, Y., Zheng, X. (2023). Impact of dissolved oxygen on the

performance and microbial dynamics in side-stream activated sludge hydrolysis process. Water, 15(11): 1977. https://doi.org/10.3390/w15111977

[23] LaGrega, M.D., Buckingham, P.L., Evans, J.C. (2001). Hazardous Waste Management. Waveland Press, Inc., United States of America.

[24] Mustamin, N., Isa, I., Solang, M., Lamondo, D., Kandowangko, N.Y., Baderan, D.K. (2015). Bioabsorption of heavy metal of lead (Pb) by water hyacinth plant (Eichhornia crassipes) with different contact time. https://repository.ung.ac.id/skripsi/show/431411062/bioabsorbsi-logam-berat-timbal-pb-oleh-tumbuhan-eceng-gondok-eichhornia-crassipes-dengan-waktu-kontak-yang-berbeda.html#, accessed on Apr. 22, 2024.

[25] Chaffai, R., Koyama, H. (2011). Chapter 1 - Heavy metal tolerance in Arabidopsis thaliana. In: Advances in Botanical Research, 60: 1-49. https://doi.org/10.1016/B978-0-12-385851-1.00001-9

[26] Shukla, D., Trivedi, P.K., Nath, P., Tuteja, N. (2016). Metallothioneins and phytochelatins: Role and perspectives in heavy metalloids stress tolerance in crop plants. In: Tuteja, N., Gill, S.S. (eds), Abiotic Stress Response in Plants. https://doi.org/10.1002/9783527694570.ch12

[27] Li, J., Zhang, M., Sun, J., Mao, X., Wang, J., Liu, H., Zheng, H., Li, X., Zhao, H., Zou, D. (2020). Heavy metal stress-associated proteins in rice and arabidopsis: Genome-wide identification, phylogenetics, duplication, and expression profiles analysis. Frontiers in Genetics, 11: 237-264. https://doi.org/10.3389/fgene.2020.00477

[28] Ali, E., Shah, H., Jalal, F., Khan, M.A., Imtiaz, M., Said, F., Ismail, M., Khan, S., Ali, H.M., Hatamleh, A A., Al-Dosary, M.A., Mosa, W.F.A., Shah, F. (2023). Salicylic acid-mitigates abiotic stress tolerance via altering defense mechanisms in Brassica napus (L.). Frontiers in Plant Science, 14. https://doi.org/10.3389/fpls.2023.1187260

[29] Ejaz, U., Khan, S.M., Khalid, N., Ahmad, Z., Jehangir, S., Rizvi, Z.F., Lho, L.H., Han, H., Raposo, A. (2023). Detoxifying the heavy metals: A multipronged study of tolerance strategies against heavy metals toxicity in plants. Frontiers in Plant Science, 14. https://doi.org/10.3389/fpls.2023.1154571

[30] Raza, A., Ashraf, F., Zou, X., Zhang, X., Tosif, H. (2020). Plant adaptation and tolerance to environmental stresses: Mechanisms and perspectives. In: Hasanuzzaman, M. (eds), Plant Ecophysiology and Adaptation under Climate Change: Mechanisms and Perspectives I, pp. 117-145. https://doi.org/10.1007/978-981-15-2156-0_5