Bindura University of Science Education

Phytoremediation of acid mine wastewater using aquatic plants: a case study of a gold mine in Chanaka.

By

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Approval form

The undersigned certify that they have read the dissertation titled 'Phytoremediation of acid mine wastewater using aquatic plants: a case study of a gold mine in Chanaka' and confirm that it is suitable for submission to the Biological Sciences Department, Faculty of Science and Engineering, for assessment.

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Declaration

I, Melissa Manyinyire (B212781B) declare that this research herein is my own work and has not been plagiarized from another source(s) without acknowledgement of the concerned author(s) either electronically or otherwise

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Supervisor

I, E. Zingoni, declare that I have supervised this thesis and I am satisfied that it can be submitted to the Biological Sciences Department, Faculty of Science and Engineering, at Bindura University of Science Education.

Signature: E.Z Date: 17-06-25

Dedication

I dedicate this work to my loving family, whose unwavering support and encouragement have been my strength throughout this academic journey.

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List of abbreviations

AAS – Atomic Absorption Spectrophotometer
ANOVA – Analysis of Variance
Cd - Cadmium
Cu - Copper
Fe - Iron
Pb - Lead
HN0 – Nitric acid
NTU- Nephelometric Turbidity Units
SDGs – Sustainable Development Goals
UV- Ultraviolet
UV-Vis – Ultraviolet-Visible Spectrophotometer

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Abstract

Acid mine wastewater contains high concentrations of heavy metals and has a low pH, making it harmful to aquatic life and human health. In Bindura, gold mining is a major contributor to such pollution. Conventional treatment methods are often expensive and ineffective, prompting interest in sustainable solutions like phytoremediation. This study investigates the potential of three aquatic plants, water hyacinth (*Eichhornia crassipes*), duckweed (*Lemna minor*) and salvinia (*Salvinia molesta)* to remediate acid mine wastewater. Water samples were collected from a gold mine in Chanaka, an area found in Bindura. Healthy specimens of each plant species were acclimatized and then exposed to the wastewater in 10 litre containers over a period of 28 days. Each treatment was replicated three times. Thereafter, weekly water samples were collected and analysed for pH, turbidity, heavy metals (Pb, Cd, Fe, Cu) and nutrients (nitrate and phosphate) using standard procedures, including atomic absorption spectroscopy for metal quantification. The results showed that all three aquatic plants contributed to improvements in water quality, but *Eichhornia crassipes* demonstrated the highest overall removal efficiency across all measured parameters. It raised the pH from 3.2 to 6.1 and reduced turbidity by 68%. Metal removal efficiencies for *Eichhornia crassipes* were Pb (84%), Cd (79%), Fe (88%) and Cu (81%) along with notable reductions in nitrate (65%) and phosphate (58%). *Lemna minor* and *Salvinia molesta* were less effective but still contributed significantly to pollutant removal. Although *Eichhornia crassipes* outperformed the other species, one-way ANOVA showed no statistically significant differences ($p>0.05$) in removal efficiencies among the plant species. The study concludes that aquatic macrophytes, particularly *Eichhornia crassipes* offer a low cost and environmentally friendly approach for improving the quality of acid mine wastewater. These findings support the adoption of phytoremediation as a sustainable alternative for managing water bodies impacted by mining activities.

Contents

Chapter 1
Introduction

1.1 Background

Acid mine wastewater poses a significant environmental and health risk globally (Sinha et al., 2020). The mining industry generates large volumes of wastewater contaminated with heavy metals, acidity and other pollutants (Kumar et al., 2018). Acid mine wastewater is characterized by high levels of heavy metals, acidity and other pollutants which can have devastating effects on aquatic ecosystems and human health (Moyo et al., 2019).

The mining sector in Zimbabwe is a major contributor to the national economy, although it also presents significant environmental and health risks (Moyo et al., 2019). Bindura town host substantial gold mining ventures by both small scale and large scale miners. Their mining activities produce large volumes of wastewater that requires treatment before discharge into the environment.

Phytoremediation, a cost-effective and eco-friendly approach, has gained attention for treating acid mine wastewater (Saha et al., 2017). It is a process that uses plants to clean up contaminated water, soil or sediment. Phytoremediation is a sustainable and eco-friendly approach to treating wastewater, which involves the use of aquatic plants to remove pollutants from contaminated water (Adegoke et al., 2017). It is an alternative to traditional methods of remediation as it harnesses the natural ability of plants to absorb pollutants and degrade them. Aquatic plants like water hyacinth, duckweed and salvinia have shown potential for removing heavy metals and improving water quality (Sharma et al., 2018; Singh et al., 2019). These plants have been proposed as effective agents for phytoremediation due to their efficient nutrient uptake (Adegoke et al., 2017). These plants are very effective in removing heavy metals and other pollutants from wastewater (Luo et al., 2020). These plants are easy to cultivate, require minimal maintenance and can thrive in contaminated water, making them ideal for phytoremediation (da Silva et al., 2021). Water hyacinth scientifically known as *Eichhornia crassipes* is a free-flowing aquatic plant that has been widely used for phytoremediation of wastewater. It has a high growth rate. It can absorb large amounts of heavy metals and can tolerate high levels of acidity (Upadhyay et al., 2020). Duckweed scientifically known as *Lemna minors* an aquatic plant that has been used for phytoremediation. It has a high growth rate, can absorb heavy metals and can tolerate high levels of acidity. Salvinia scientifically known *Salvinia molesta* is a floating aquatic fern that has been used for phytoremediation. It has a high growth rate, and it can absorb heavy metals and can tolerate high levels of acidity.

1.2 Problem Statement

The mining activities in Bindura generate large volumes of acid mine wastewater, posing a significant threat to the environment and human health (Mapani et al., 2020). The wastewater is characterized by high levels of heavy metals, acidity and other pollutants, which can have devastating effects on aquatic ecosystems and human health (Nkomo et al., 2018). The discharge of acid mine wastewater into water sources not only harm aquatic life but also contaminate soil, and air leading to broader environmental degradation.

Furthermore, exposure to acid mine wastewater pollutants can cause severe health problems, including respiratory issues, cancer and many more health complications which then puts the community at risk (Mishra et al 2018). Current treatment methods are expensive, energy- intensive and ineffective in removing heavy metals and other pollutants (Mokone et al., 2021). A sustainable and eco-friendly approach, such as phytoremediation is needed to address this environmental concern.

1.3 Aim of the Study

To investigate the potential of water hyacinth (*Eichhornia crassipes)*, duckweed (*Lemna minor)* and salvinia (*Salvinia molesta)* to remove pollutants from acid mine wastewater collected from a gold mine in Chanaka, Bindura

1.4 Objectives of the Study

1. Determine pollutant removal efficiency of water hyacinth *(Eichhornia crassipes*), duckweed (Lemna *minor*) and salvina (*Salvinia molesta).*
2. Determine specific heavy metals removed from mine wastewater by water hyacinth *(Eichhornia crassipes*), duckweed (*Lemna minor*) and salvina (*Salvinia molesta).*
3. Compare the effectiveness of *Eichhornia crassipes, Lemna minor* and *Salvinia molesta* in improving the overall quality of acid mine wastewater and identify the species with the highest remediation potential.

1.5 Research Questions

1. Can water hyacinth *(Eichhornia crassipes*), duckweed (Lem*na minor*) and salvina (*Salvinia molesta*) remove heavy metals and other pollutants from gold acid mine wastewater?
2. Which pollutants are removed from mine wastewater by water hyacinth, duckweed and salvina?
3. Which plant species is most effective in removing pollutants and improving water quality?

1.6 Justification of Research

Phytoremediation is a vital approach to removing pollutants from contaminated water and soil, utilizing plants to absorb, degrade pollutants in a cost-effective and environmentally friendly manner. The importance of phytoremediation lies in its ability to remove heavy metals and other pollutants from wastewater, improving water quality and reducing the risk of environmental and health impacts. Additionally, phytoremediation can restore degraded ecosystems and habitats, promote biodiversity and ecosystems services. This research is crucial because wastewater is a significant environmental and health concern in Zimbabwe, and phytoremediation offers a sustainable solution for its treatment. Furthermore, the mining industry is a significant contributor to Zimbabwe's economy and phytoremediation can help reduce its environmental footprint. By investigating the potential of aquatic plants for remediation of gold acid mine wastewater, this research aims to contribute to the development of sustainable and eco-friendly solutions for wastewater treatment, aligning with the Sustainable Development Goals (SDGs) 6, 12 and 15 which focus on clean water and sanitation, responsible consumption and life on land, respectively.

1.7 Hypothesis

H_0 There is no significant difference in the ability of water hyacinth (*Eichhornia crassipes)*, duckweed (*Lemna minor)* and salvinia (*Salvinia molesta)* to remove heavy metals and other pollutants from acid mine wastewater.

H_1 There is a significant difference in the ability of water hyacinth (*Eichhornia crassipes)*, duckweed (*Lemna minor)* and salvina (*Salvinia molesta)* to remove heavy metals and other pollutants from acid mine wastewater.

1.8 Limitations

This study has several limitations that may impact the results and conclusions. One major limitation is the time constraint, as the study will be conducted within a limited timeframe, which may not allow for a comprehensive analysis of the phytoremediation process. Additionally, the sample size may be limited, which could impact the generalizability of the results. Controlling environmental factors such as temperature factors such as temperature, light and nutrient availability may also be challenging which could affect plant growth and pollutant removal. Finally, the study will only investigate a few plant species which may not be representative of all aquatic plants with phytoremediation potential.

1.9 Delimitations

The study focuses on acid mine wastewater and does not consider other types of wastewater. Furthermore, the study only investigates water hyacinth, duckweed and salvinia and other plants species with potential for phytoremediation are not considered. The study primarily focuses on heavy metals and acidity, and other pollutants present in the wastewater are not addressed. By acknowledging these delimitations, the study aims to provide a focused and in-depth investigation of phytoremediation in a specific context.

Chapter 2

Literature review

2.1 Introduction

Phytoremediation is a sustainable technology for cleaning contaminated environments using plants. There has been a surge in pollutants that threaten ecosystems and human health with, heavy metals from industrial activities, particularly mining. Acid mine wastewater, often characterized by high acidity and heavy metal content, poses a significant environmental challenge. This review explores the development and application of phytoremediation, focusing on the role of aquatic plants such as water hyacinth (*Eichhornia crassipes*), duckweed *(Lemna minor*), and salvinia (*Salvinia molesta*) in the removal of pollutants from contaminated water (Ali et al., 2013; Yan et al., 2020).

2.2 Acid Mine Wastewater and Its Environmental Impact

Acid mine wastewater results from mining activities, primarily involving the oxidation of sulphide minerals, leading to the release of sulfuric acid and dissolved metals into water bodies. According to Kumar et al. (2018), acid mine wastewater is characterized by low pH and high concentrations of heavy metals such as iron, lead, copper, and cadmium. If untreated, it poses risks to aquatic ecosystems, agricultural land, and drinking water sources. Moyo et al. (2019) emphasized the importance of cost-effective treatment technologies in regions like Bindura, where gold mining is prevalent.

2.3 Traditional Methods of Treating Acid Mine Wastewater

Conventional treatment methods for acid mine wastewater, such as chemical precipitation, ion exchange, and reverse osmosis, are often costly, energy-intensive, and produce secondary pollution (Mapani et al., 2020). These methods, while effective in some contexts, struggle to address the large-scale and continuous generation of wastewater from mining activities. As such, there is growing interest in more sustainable and eco-friendly solutions like phytoremediation (Singh et al., 2019; Verma et al., 2016).

2.4 Phytoremediation: An Overview

Phytoremediation uses plants to remove, transfer, stabilize, and destroy contaminants in soil and water. It is appealing because of its low cost, minimal environmental disruption, and ability to restore ecosystems (Sharma et al., 2018; Ali et al., 2013). It works through several pathways such as phytoextraction which is when plants absorb contaminants through their roots and store them in their shoots and leaves. Phytodegradation is when plants degrade pollutants through metabolic processes. Phyto stabilization is when plants immobilize contaminants, preventing their movement through the soil or water. Rhizofiltration is when plant roots filter out pollutants from aqueous environments.

2.5 Aquatic Plants in Phytoremediation

Aquatic plants demonstrate strong potential in phytoremediation due to their ability to grow in water and tolerate high levels of pollutants. According to Adegoke et al. (2017), plants such as water hyacinth, duckweed, and salvinia have been the focus of numerous studies for their pollutant absorption capacities, particularly in areas affected by mining activities. Liu et al. (2021) further emphasized the suitability of floating macrophytes in constructed wetlands for heavy metal removal.

2.5.1 Water Hyacinth (*Eichhornia crassipes*)

Water hyacinth is considered highly effective plants for the phytoremediation of heavy metals. According to Upadhyay et al. (2020), it can absorb large amounts of heavy metals, including cadmium, lead, and mercury, through its roots. Its high growth rate and tolerance to acidic environments make it suitable for wastewater treatment. Studies by Ibrahim et al. (2020) have shown that water hyacinth can reduce pollutant concentrations by over 50% in some instances. Mbululo and Dlamini (2022) highlighted the effectiveness of *Eichhornia crassipes* in Southern African mining regions, especially for iron and copper uptake.

2.5.2 Duckweed (*Lemna minor*)

Duckweed, another fast-growing aquatic plant, is commonly applied in treating wastewater. Sharma et al. (2018) demonstrated that duckweed could remove heavy metals such as copper and zinc from wastewater with a high degree of efficiency. Its small size, rapid biomass production, and ability to thrive in nutrient-limited environments make it suitable for large-scale remediation efforts (Zayed et al., 1998).

2.5.3 Salvinia (*Salvinia molesta*)

Salvinia molesta is a floating aquatic fern with a high capacity for metal uptake. Singh et al. (2019) reported that salvinia could tolerate extreme acidity and absorb metals such as iron, manganese, and aluminium from contaminated water. Its adaptability and rapid colonization potential make it an excellent candidate for phytoremediation, particularly in acidic mine-impacted water bodies (Yan et al., 2020).

2.6 Mechanisms of Pollutant Removal by Aquatic Plants

Aquatic plants remove pollutants through several mechanisms. According to Saha et al. (2017), the roots of these plants provide large surface areas for the adsorption of metal ions. The metals are then absorbed and either accumulated in the plant tissue or precipitated in the root zone, effectively reducing the concentration of pollutants in the water. Studies by da Silva et al. (2021) showed that the effectiveness of this process depends on factors such as plant species, pollutant type, water chemistry, and environmental conditions. Liu et al. (2021) further suggest that microbial interactions in the rhizosphere can enhance nutrient and metal removal in floating macrophyte systems.

2.7 Comparative Effectiveness of Aquatic Plants in Phytoremediation

The effectiveness of phytoremediation varies depending on the plant species and the nature of the contaminants. Comparative studies by Mokone et al. (2021) and Novita et al. (2020) revealed that water hyacinth was more effective in removing heavy metals compared to duckweed and salvinia. However, duckweed exhibited faster growth rates, which may offset its lower metal uptake efficiency in large-scale applications. Ali et al. (2013) noted that combining species in treatment systems could enhance performance through complementary uptake pathways.

2.8 Challenges in Phytoremediation

Despite its many advantages, phytoremediation faces several challenges. The time required for significant pollutant removal can be long, particularly for large-scale contamination (Kumar et al., 2018). Environmental factors such as temperature, light availability, and nutrient levels can affect the growth and pollutant absorption rates of plants. Furthermore, there is the issue of biomass disposal, as the accumulated metals in plant tissues can create secondary pollution risks if not handled properly (Sinha et al., 2020). Yan et al. (2020) recommended integrating phytoremediation with post-treatment options like composting or energy recovery to manage contaminated biomass.

2.9 The Role of Phytoremediation in Sustainable Development

Phytoremediation aligns with global sustainability goals, particularly those related to clean water and sanitation (SDG 6), responsible consumption (SDG 12), and life on land (SDG 15). By integrating phytoremediation into wastewater management strategies, regions affected by mining activities can mitigate environmental damage while promoting biodiversity and ecological restoration (Mapani et al., 2020; Verma et al., 2016).

Chapter 3

Materials and methods

3.1 Introduction

The success of this study depends on designing a controlled experiment to evaluate the phytoremediation potential of *Eichhornia crassipes* (water hyacinth), *Lemna minor* (duckweed), and *Salvinia molesta* (salvinia) in removing heavy metals and pollutants from acid mine wastewater. This chapter outlines the materials, methods, and procedures that will be used to conduct the study, including plant selection, wastewater collection, experimental setup, water quality analysis, and data analysis.

3.2 Study Area

The wastewater samples for this study were collected from a gold mine in Chanaka, located in the Bindura region. The area is situated within the Mazowe Valley, characterized by a semi-arid climate with annual rainfall ranging between 650mm and 900mm. the average temperature ranges from 15°C in winter to 30 °C in summer. The geology of the area comprises greenstone belts rich in gold-bearing quartz reefs and the soils are mainly derived from granite and gneiss. The soils are generally sandy to loamy in texture (Manatsa et al., 2020).

Sampling was conducted at a goldmine in Chanaka, just outside Bindura town (Latitude: -17.3019°, Longitude: 31.3306°). The experimental study was conducted at the University of Zimbabwe, Department of Biological Sciences, where controlled conditions were maintained to assess the phytoremediation potential of selected aquatic plants.

3.3 Experimental Design

3.3.1 Plant Selection and Preparation

Healthy plants of *Eichhornia crassipes, Lemna minor*, and *Salvinia molesta* were sourced from pot plants at the University of Zimbabwe, which were maintained to mimic natural water bodies. Aquatic plants specimens were selected based on uniform size, visible healthy and absence of pest or disease symptoms to minimize biological variability across treatments. All plants were washed with distilled water to remove any external contaminants or debris. The roots were inspected for any damage before being used in the experiment.

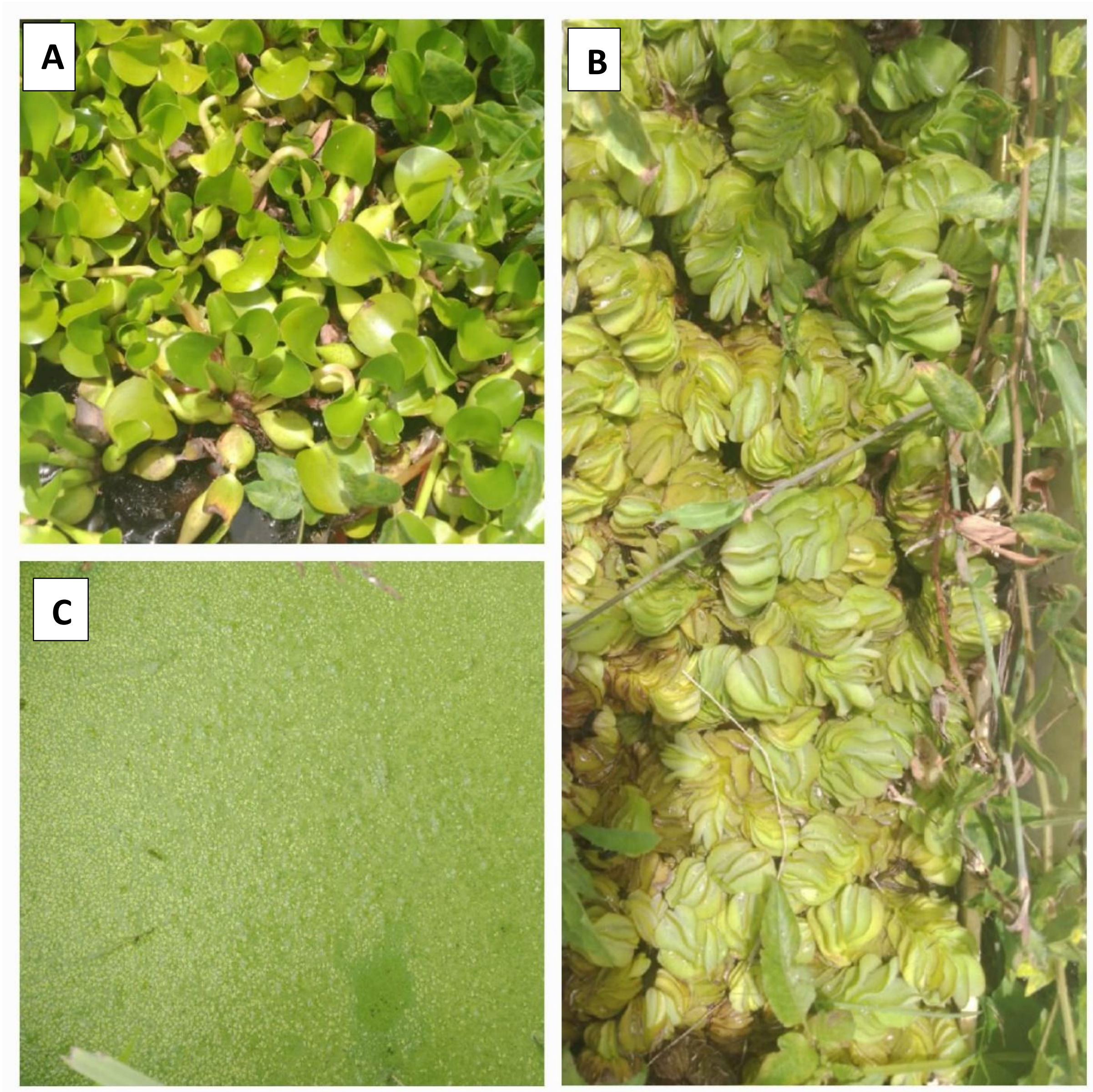

Figure 1: Aquatic plants (water hyacinth (A), Salvinia (B) and duckweed (C) before the experiment

3.3.2 Wastewater Sample Collection

Acid mine wastewater samples were collected from active gold mine site in Bindura using clean, sterile containers. Samples were collected at the tailings' pond at Chanaka mine. A purposive sampling method was employed for wastewater collection. Samples were obtained from the most visibly contaminated zones within the mine tailings pond to ensure representation of peak pollution levels as shown in Figure 3 below.

Figure 2: Gold mine wastewater collection site in Chanaka, Bindura

The samples were transported to the laboratory at the University of Zimbabwe. Before the experiment, the collected wastewater samples were analyzed for initial pH, turbidity, and heavy metal concentrations (such as lead, cadmium, iron, and copper) using the pH meter, turbidity meter, and AAS.

Experimental Setup

A total of 4 aquarium tanks were set up, with each plant species (water hyacinth, duckweed, and salvinia) being tested. Each container was filled with 10 liters of collected acid mine wastewater. The containers were placed in a controlled environment with constant lighting (12 hours of daylight and 12 hours of darkness) and ambient temperature (25-30°C). Water temperature will be monitored regularly using a digital thermometer. The temperature was maintained using air conditioning.

Figure 3: Experimental setup at the University of Zimbabwe, Department of Biological Sciences

3.3.4 Monitoring and Sampling

The experiment was run for 28 days, with sampling taking place at four intervals: Day 7, Day 14, Day 21, and Day 28. At each sampling interval, water samples were collected from each container to analyze changes in pH, turbidity, heavy metal concentrations, and nutrient levels.

3.3.5 Heavy Metal Concentration

To determine the concentrations of lead, cadmium, iron and copper, 100ml of water was collected from each tank at every sampling interval and filtered using 0.45pm membrane filters to remove suspended solids. Each filtrate was acidified by adding 2ml of concentrated nitric acid (69% HNO_3) to stabilize the metal ions. The acidified samples were digested on a hot plate at 95°C for two hours to break down any organic material and ensure complete metal solubilization. After cooling, the digested solutions were quantitatively transferred into 1000ml volumetric flasks, and it was filled with deionized water. Calibration standards were prepared by diluting certified

1000mg/L stock solutions of each metal to produce five standards of concentrations 0.5mg/L, 1.0mg/L, 2.0mg/L, 4.0mg/L, and 6.0mg/L. these were also acidified and processed under the same conditions as the samples. The prepared samples were then sent to the University of Zimbabwe, Department of Mining Engineering where they were analyzed using an Atomic Absorption Spectrophotometer (AAS). The AAS was calibrated with the standards and absorbance readings were recorded for each metal at their respective wavelengths (Pb at 217.0nm, Cd at 228.8nm, Fe at 248.3nm and Cu at 324.8nm). The concentrations of metals were calculated using the corresponding standard calibration curves.

3.3.6 Nutrient Levels

To determine the concentrations of nitrogen and phosphorus, 50ml of each was collected from the tanks at each sampling level. The samples were filtered using 0.45pm membrane filters to remove suspended solids. For nitrogen analysis, the cadmium reduction method was applied whereby nitrate was reduced to nitrite and then reacted with sulfanilamide and N-(1-naphthyl)-ethylenediamine (NED) to produce a pink azo dye measured at 543nm. For phosphorus the ascorbic acid method was used whereby a reaction was made by mixing ammonium molybdate and ascorbic acid to form a blue complex was measured at 880nm. Absorbance values were compared against calibration curves prepared using standard solutions of known concentrations. The measurements were conducted using a UV spectrophotometer, this allowed for accurate determination of nutrient levels and evaluation of the nutrient removal efficiency of each aquatic plant species.

3.5 Data Analysis

3.5.1 Pollutant Removal Efficiency

The pollutant removal efficiency for each plant species was calculated using the following formula:

$$Removal\ Efficiency\ \% = \frac{initial\ conc - final\ conc}{initial\ conc} \times 100$$

This was calculated for each heavy metal (lead, cadmium, iron and copper) and overall pollutant removal.

3.5.2 Comparison of Plant Effectiveness

A comparative analysis of the pollutant removal efficiencies between *Eichhornia crassipes*, *Lemna minor*, and *Salvinia molesta* was conducted. Statistical analysis (e.g., ANOVA) was used to determine if there are significant differences in the phytoremediation capacities of the three species. Further comparison was also used to consider changes in water quality parameters such as pH and turbidity.

3.5.3 Statistical Analysis

One-way ANOVA was selected for statistical analysis as it is suitable for comparing the means of more than two groups, in this case the three plant species. This method helps determine whether observed differences in pollutant removal are statistically significant beyond random variation.

Chapter 4

Results

4.1 Introduction

This chapter presents the results of the phytoremediation experiment conducted to assess the ability of water hyacinth (*Eichhornia crassipes*), duckweed (*Lemna minor*), and salvinia (*Salvinia molesta*) to remove heavy metals from acid mine wastewater. The results include changes in water quality parameters such as pH, turbidity, heavy metal concentrations and nutrient levels over the 28-day period.

4.2 Changes in Water Quality

4.2.1 pH Variations

The pH of the acid mine wastewater was measured at 1, 7, 14, 21 and 28 days. The results show a gradual change in pH, with water hyacinth demonstrating the highest improvement.

Table 1: pH values of acid mine wastewater treated with water hyacinth, duckweed and salvinia over a 28-day period.

Day	Water hyacinth	Duckweed	Salvinia
1	3.5	3.5	3.5
7	3.7	3.6	3.6
14	4.1	3.9	3.7
21	4.4	4.1	3.9
28	5.2	4.3	4.2

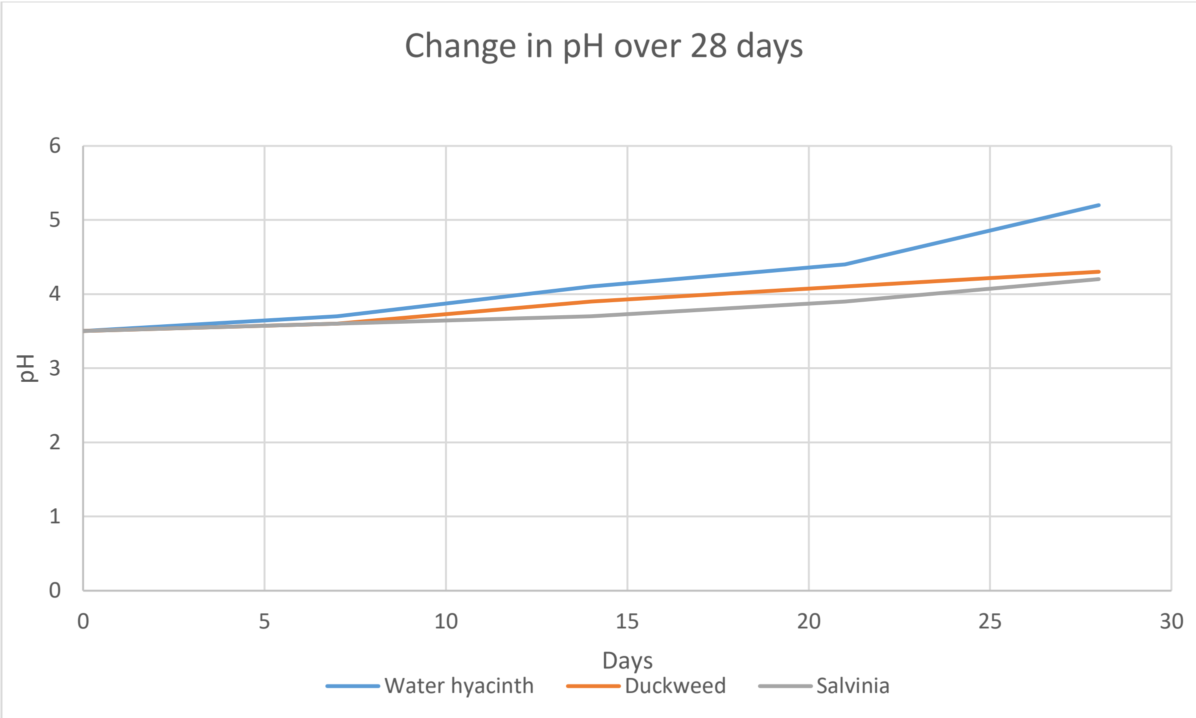

Figure 3: Change in pH over 28 days in wastewater treated with three aquatic plants

As shown in Table 1, pH levels increased gradually in all plant treatments over 28 days. Water hyacinth was the most effective, increasing pH from 3.5 to 5.2 followed by duckweed (4.3) and salvinia (4.2). This trend suggests water hyacinth has the strongest capacity to neutralize acidity in acid mine wastewater.

4.3 Heavy Metal Removal

The concentrations of lead (Pb), cadmium (Cd), iron (Fe) and copper (Cu) in the wastewater was monitored over 28 days. The removal efficiency was calculated using the equation.

$$Removal\ Efficiency\,\% = \frac{initial\ conc - final\ conc}{initial\ conc} \times 100$$

4.3.1 Lead (Pb) Removal

Table 2: Lead (Pb) concentrations (mg/L) in acid mine wastewater treated with three aquatic plants over 28 days.

Day	Water Hyacinth	Duckweed	Salvinia
1	8.03 ± 0.06	8.00 ± 0.10	8.00 ± 0.10
7	7.27 ± 0.15	6.40 ± 0.10	6.80 ± 0.10
14	4.50 ± 0.20	4.80 ± 0.10	5.40 ± 0.10
21	3.20 ± 0.10	3.40 ± 0.10	3.90 ± 0.10
28	2.20 ± 0.10	2.40 ± 0.10	2.90 ± 0.10

The concentration of lead in acid mine wastewater decreased consistently across all plant treatments over the 28-day period. *Eichhornia crassipes* (water hyacinth) exhibited the highest Pb removal efficiency, with concentrations declining from 8.03 ± 0.06 mg/L on Day 1 to 2.20 ± 0.10 mg/L by Day 28. *Lemna minor* (duckweed) reduced Pb from 8.00 ± 0.10 mg/L to 2.40 ± 0.10 mg/L, while *Salvinia molesta* achieved a reduction from 8.00 ± 0.10 mg/L to 2.90 ± 0.10 mg/L. Although water hyacinth showed superior performance overall, one-way ANOVA revealed no statistically significant differences in Pb removal among the three plant species ($p > 0.05$).

4.3.2 Cadmium (Cd) Removal

Table 3: Cadmium (Cd) concentrations (mg/L) in acid mine wastewater treated with three aquatic plants over 28 days.

Day	Water Hyacinth	Duckweed	Salvinia
1	2.00 ± 0.10	2.03 ± 0.10	2.00 ± 0.00
7	1.40 ± 0.10	1.50 ± 0.10	1.60 ± 0.10
14	0.90 ± 0.10	1.10 ± 0.10	1.30 ± 0.10
21	0.50 ± 0.10	0.70 ± 0.10	1.00 ± 0.10

28	0.43 ± 0.06	0.60 ± 0.10	0.80 ± 0.10

All three aquatic plants significantly reduced cadmium concentrations(p value of 0.33) in the wastewater over 28 days. *Eichhornia crassipes* (water hyacinth) reduced Cd from 2.00 ± 0.10 mg/L to 0.43 ± 0.06 mg/L, representing the highest overall removal efficiency. *Lemna minor* (duckweed) followed, decreasing Cd from 2.03 ± 0.10 mg/L to 0.60 ± 0.10 mg/L, while *Salvinia molesta* reduced Cd from 2.00 ± 0.00 mg/L to 0.80 ± 0.10 mg/L. Despite these observed differences, one-way ANOVA showed no statistically significant variation among the three treatments ($p > 0.05$).

4.3.3 Iron (Fe) Removal

Table 4: Iron (Fe) mean concentrations (mg/L) in acid mine wastewater treated with three aquatic plants over 28 days.

Day	Water Hyacinth	Duckweed	Salvinia
1	80.00 ± 1.00	80.00 ± 1.00	80.00 ± 0.00
7	56.00 ± 1.00	59.00 ± 1.00	64.00 ± 1.00
14	32.00 ± 1.00	35.00 ± 1.00	42.00 ± 1.00
21	16.00 ± 1.00	19.00 ± 1.00	28.00 ± 1.00
28	10.00 ± 1.00	14.00 ± 1.00	20.00 ± 1.00

A substantial reduction in iron concentrations was observed in all treatments over the 28-day period. *Eichhornia crassipes* lowered Fe levels from 80.00 ± 1.00 mg/L to 10.00 ± 1.00 mg/L, showing the highest efficiency. *Lemna minor* reduced Fe from 80.00 ± 1.00 mg/L to 14.00 ± 1.00 mg/L, while *Salvinia molesta* showed the lowest removal, decreasing Fe from 80.00 ± 0.00 mg/L to 20.00 ± 1.00 mg/L. Despite the effectiveness of all three species, one-way ANOVA indicated no statistically significant differences in iron removal efficiencies ($p > 0.05$).

4.3.4 Copper (Cu) Removal

Table 5: Copper (Cu) concentrations (mg/L) in acid mine wastewater treated with three aquatic plants over 28 days.

Day	Water Hyacinth	Duckweed	Salvinia
1	5.00 ± 0.10	5.00 ± 0.10	5.00 ± 0.00
7	3.80 ± 0.10	4.00 ± 0.10	4.30 ± 0.10
14	2.50 ± 0.10	2.70 ± 0.10	3.10 ± 0.10
21	1.40 ± 0.10	1.70 ± 0.10	2.30 ± 0.10
28	0.57 ± 0.06	0.90 ± 0.10	1.40 ± 0.10

Copper concentrations were markedly reduced in all treatments during the 28-day experiment. *Eichhornia crassipes* showed the greatest reduction, with levels falling from 5.00 ± 0.10 mg/L to 0.57 ± 0.06 mg/L. *Lemna minor* reduced copper from 5.00 ± 0.10 mg/L to 0.90 ± 0.10 mg/L, while *Salvinia molesta* showed the least reduction, from 5.00 ± 0.00 mg/L to 1.40 ± 0.10 mg/L**.** Although *Eichhornia crassipes* appeared more efficient, statistical analysis (one-way ANOVA) indicated no significant differences in copper removal among the plant species ($p > 0.05$).

4.3.4 Heavy Metal Removal Efficiency

Table 6:Heavy Metal removal Efficiency Summary

Metal	Water Hyacinth	Duckweed	Salvinia
Lead (Pb)	72.60%	70.00%	63.80%
Cadmium (Cd)	78.50%	70.40%	60.00%
Iron (Fe)	87.50%	82.50%	75.00%
Copper (Cu)	88.60%	82.00%	72.00%
Nitrates	78.00%	66.40%	61.20%
Phosphates	80.20%	70.40%	65.30%
Turbidity	88.90%	76.30%	69.50%

The overall performance of the three aquatic macrophytes in removing heavy metals from acid mine wastewater is summarized in Table 6. *Eichhornia crassipes* (water hyacinth) consistently demonstrated the highest removal efficiencies across all four metals, with removal rates of 88.6% for Cu**,** 87.5% for Fe**,** 78.5% for Cd, and 72.6% for Pb. *Lemna minor* (duckweed) followed, achieving between 70.0% and 82.5% removal across the metals, while *Salvinia molesta* showed the lowest removal performance, ranging from 60.0% to 75.0%**.**

4.3.5 Nitrate Removal

Table 7: Nitrate concentrations (mg/L) in acid mine wastewater treated with three aquatic plants over 28 days

Day	Water Hyacinth (mg/L)	Duckweed (mg/L)	Salvinia (mg/L)
1	8	8	8
7	5.8	6.4	6.9
14	3.6	4.7	3.2
21	2.1	2.8	3.6
28	1.1	1.6	2.3
Removal Efficiency	86.25%	80%	71.25%

Table 7 demonstrates the decrease in nitrate concentrations over the 28-day period. Water hyacinth was the most effective in removing nitrates, reducing levels from 8.0 mg/L to 1.1 mg/L, achieving an 86.25% removal efficiency. Duckweed followed with a reduction to 1.6 mg/L (80%), and salvinia to 2.3 mg/L (71.25%). This confirms the high potential of aquatic plants, especially water hyacinth, in removing nitrates from acid mine wastewater.

4.3.6 Phosphate Removal

Table 8: Phosphate (Pb) concentrations (mg/L) in acid mine wastewater treated with three aquatic plants over 28 days.

Day	Water Hyacinth (mg/L)	Duckweed (mg/L)	Salvinia (mg/L)
1	6	6	6
7	4.6	5.2	5.5
14	3.1	3.9	4.3
21	1.7	2.4	2.9
28	0.8	1.1	1.5
Removal Efficiency	86.67%	81.67%	75%

Table 8 show the reduction in phosphate concentrations over the 28-day period. Water hyacinth exhibited the highest removal efficiency, reducing phosphate from 6.0 mg/L to 0.8 mg/L, achieving an 86.67% removal rate. Duckweed reduced phosphate to 1.1 mg/L (81.67%) and salvinia to 1.5 mg/L (75%). This indicates that water hyacinth is particularly effective in removing phosphate, while the other plants also showed good performance.

4.3.7 Turbidity

Table 9: Turbidity concentrations (NTU) in acid mine wastewater treated with three aquatic plants over 28 days

Day	Water Hyacinth (NTU)	Duckweed (NTU)	Salvinia (NTU)
1	75	75	75
7	52	60	65
14	38	46	52
21	28	38	45
28	20	32	40
	73.33%	57.33%	46.67%

Removal Efficiency	

Table 9 illustrate the decrease in turbidity levels over the 28-day period. Water hyacinth showed the greatest reduction in turbidity, decreasing from 75 NTU to 20 NTU, with a 73.33% reduction. Duckweed reduced turbidity to 32 NTU (57.33%), and Salvinia to 40 NTU (46.67%). These results suggests that water hyacinth is highly effective in improving water quality, with duckweed and salvinia also contributing to turbidity removal.

4.4 Plant Condition and Survival Rate

The physical condition of the plants deteriorated progressively over the 28day period, indicating stress due to metal accumulation. The extent of degradation varied among the three plant species, with duckweed exhibiting the most visible damage, followed by Salvinia and Water Hyacinth.

4.4.1 Water Hyacinth Condition

Figure 4 shows water hyacinth after the experiment

At the beginning of the experiment, water hyacinth displayed vibrant green leaves, thick petioles, and a healthy structure (figure 2). However, by day 28, significant browning, wilting and leaf shrinkage were observed (figure 4).

4.4.2 Salvinia Condition

Salvinia initially had dense, buoyant, green leaves with a velvet surface (figure 2). As metal uptake progressed, the leaves became darker, curled and brittle (figure 5 below). On day 28, the floating ability had decreased, and some leaves had completely deteriorated indicating physiological stress.

Figure 5 shows Salvinia after the experiment

4.4.3 Duckweed Condition

Duckweed initially had small, bright green floating fronds (figure 2). Overtime the leaves started turning yellowish brown and a reduction in biomass was noticeable in figure 6 below. On day 28, the duckweed mat had thinned out indicating the plant’s struggle to survive in the metal laden environment.

Figure 6 shows duckweed after the experiment

Water hyacinth showed initial wilting but survived better than the other species. Some plants remained green with root elongation. Duckweed showed moderate survival but some colonies turned brown and decomposed after 14–21 days. Salvinia showed severe deterioration was noted, with most plants turning dark brown and dying within the first 14 days.

4.5 Statistical Analysis (ANOVA)

Table 10: Summary of one-way ANOVA results showing p-values for pollutant removal by aquatic plants.

Parameter	F-value	p-value	Significance
Lead (Pb)	0.161	0.85186	Not significant ($p > 0.05$)
Cadmium (Cd)	1.11	0.33888	Not significant
Iron (Fe)	0.389	0.67997	Not significant
Copper (Cu)	0.532	0.59131	Not significant

As shown in Table 10, none of the observed differences in removal efficiencies were statistically significant ($p > 0.05$). This suggests that the variation in pollutant removal across the three plant species may be due to random chance rather than a true difference in effectiveness.

Chapter 5

Discussion, Summary, Recommendations and Conclusions

5.1 Discussion

5.1.1 Overview

This chapter interprets the findings from the phytoremediation experiment, evaluating the effectiveness of water hyacinth *(Eichhornia crassipes*), duckweed (*Lemna minor*), and salvinia (*Salvinia molesta*) in treating acid mine wastewater. The discussion focuses on changes in water quality parameters, plant health observations, and the implications of these results in the context of existing literature.

5.1.2 pH Modification

All three aquatic plant species contributed to an increase in pH, with *Eichhornia crassipes* raising the pH from 3.5 to 5.2, *Lemna minor* to 4.3, and *Salvinia molesta* to 4.2. This demonstrates the plants' capacity to reduce acidity in mine wastewater. These findings are consistent with Upadhyay et al. (2020), who reported that water hyacinth can increase pH in acid mine drainage by facilitating ion exchange and buffering acidic conditions.

The improvement in pH is particularly critical, as acidic conditions are known to increase the mobility of toxic metals in water bodies (Zhou et al., 2015). By raising pH, these plants not only improve water quality but also promote the precipitation of metal ions, thus enhancing overall pollutant removal. Among the species, *Eichhornia crassipes* showed the highest buffering capacity, likely due to its dense root system and higher biomass, which promotes greater ion exchange.

5.1.3 Heavy Metal Removal Efficiency

Eichhornia crassipes exhibited the highest removal efficiency for all metals analysed — lead (Pb), cadmium (Cd), iron (Fe), and copper (Cu). Similar removal patterns of iron and copper by *Eichhornia crassipes* were documented in Southern Africa by Mbululo and Dlamini (2022), reinforcing its applicability in regional mine wastewater treatment. This supports findings by Ibrahim et al. (2020), who documented high metal uptake by water hyacinth due to its extensive root surface area and high biomass. *Lemna minor* and *Salvinia molesta* showed moderate and low metal removal efficiencies, respectively. The observed ability of aquatic plants to accumulate heavy metals supports the mechanism of phytoextraction described by Ali et al. (2013), where metals are absorbed and translocated to aerial parts.

These results align with Sharma et al. (2018) and Singh et al. (2019), who observed that duckweed and salvinia are effective metal accumulators but are less tolerant to acidic conditions, which can limit their performance in extreme environments. The removal mechanisms likely involve phytoextraction and adsorption onto root surfaces, as reported by Zayed et al. (1998). Despite these observed differences, statistical analysis using one-way ANOVA indicated no significant variation in removal efficiency among the plant species ($p > 0.05$ for all metals). This suggests that the observed performance patterns may be due to biological variability rather than statistically confirmed superiority. Similar findings have been reported by Moyo et al. (2019), who emphasized the role of experimental conditions and replication in determining the statistical significance of phytoremediation outcomes. Therefore, although *Eichhornia crassipes* showed superior average removal, all three macrophytes demonstrated practical effectiveness in metal reduction under the experimental conditions.

5.1.4 Turbidity Reduction

Turbidity was most effectively reduced in tanks containing *Eichhornia crassipes*, which likely benefited from its large, fibrous root system that trapped suspended solids. The ability of water hyacinth to reduce turbidity is well-documented, including by Saha et al. (2017), who emphasized its filtering effect and role in improving water clarity. *Lemna minor* and *Salvinia molesta* also contributed to turbidity reduction but were less effective, likely due to their smaller biomass and root surface area.

Turbidity reduction is essential for improving light penetration and supporting aquatic life. The observed results suggest that even if metal removal is comparable, the physical traits of water hyacinth — such as its capacity to form dense mats — give it a clear advantage in reducing suspended solids. However, the lack of statistical significance from the ANOVA test again highlights the need for more replicates in future trials to validate this trend.

5.1.5 Nutrient Removal

The removal of nitrate and phosphate was achieved to varying degrees by all three species, with *Eichhornia crassipes* again leading in effectiveness. This is consistent with da Silva et al. (2021), who found water hyacinth highly efficient in removing excess nutrients from wastewater. Duckweed also demonstrated good nutrient uptake capacity, supporting observations by Sharma et al. (2018). *Salvinia molesta* had the lowest nutrient removal, which may be attributed to its stress response in highly acidic and metal-laden environments.

Aquatic plants absorb nitrate and phosphate through their roots and convert them into plant biomass. The higher removal by water hyacinth may also be linked to its larger surface area for microbial colonization, which enhances nitrogen and phosphorus cycling (Zhao et al., 2020). Despite these trends, ANOVA tests indicated that nutrient removal differences among species were not statistically significant ($p > 0.05$), possibly due to biological variability.

5.1.6 Plant Health and Survival

Observations of plant health revealed that water hyacinth maintained a higher survival rate and exhibited less stress compared to duckweed and salvinia. The reduced effectiveness of Salvinia in acidic conditions could relate to stress responses noted in aquatic macrophytes under similar conditions (Yan et al., 2020). The resilience of water hyacinth in acidic and contaminated environments may be due to its adaptive physiological mechanisms, including antioxidant activity and cellular tolerance to heavy metal stress (Yadav et al., 2010).

In contrast, the higher mortality rates in *Lemna minor* and *Salvinia molesta* suggest a lower tolerance to the harsh conditions of acid mine wastewater, which could limit their applicability in such settings. These findings highlight the need to select species not only for their pollutant uptake potential but also for their ability to survive in highly toxic environments over time.

5.1.7 Environmental and Ecological Considerations

While *Eichhornia crassipes* proved highly effective in treating acid mine wastewater, it is important to recognize its invasive nature. Water hyacinth is considered an invasive species in many regions, including parts of Africa and North America, where it can disrupt local ecosystems by outcompeting native vegetation (Nair & Karthikeyan, 2021). Therefore, its use in phytoremediation should be carefully managed to prevent ecological damage. Containment strategies such as using enclosed systems or controlled wetlands, should be explored to mitigate the risks associated with its introduction into natural water bodies. On the other hand, *Lemna minor* and *Salvinia molesta* are less invasive and could be better suited for use in open water systems, though they may require further investigation to assess their long-term viability in large-scale applications.

5.2 Summary

This study set out to assess the phytoremediation capabilities of *Eichhornia crassipes, Lemna minor and Salvinia molesta* in treating acid mine wastewater from a gold mine site in Bindura. Over a 28-day period, all three species contributed to measurable improvements in water quality, including reductions in heavy metal concentrations, turbidity and acidity. Among them, *Eichhornia crassipes* demonstrated the highest average removal efficiencies across most parameters, likely due to its robust root system and tolerance to harsh conditions. While one-way ANOVA showed no statistically significant differences in pollutant removal among the plant species, the observed trends point to practical variation in their effectiveness. These findings support the suitability of aquatic macrophytes as a sustainable, low-cost solution for treating acid mine wastewater, particularly in mining regions like Bindura.

5.3 Recommendations

Based on the findings of this study, it is recommended that water hyacinth be considered for pilot-scale and field-based phytoremediation of acid mine wastewater, especially in mining-affected regions of Zimbabwe. However, its use should be regulated to prevent its uncontrolled spread in natural water systems. Duckweed may be used in milder wastewater environments or in combination with water hyacinth for complementary effects. Further research should explore the long-term efficiency of these plants in natural field conditions, assess seasonal impacts on phytoremediation performance, and develop safe, low-cost methods for disposing of or repurposing the harvested plant biomass after pollutant accumulation.

This study contributes valuable baseline data for integrating phytoremediation into Zimbabwe’s environmental management strategies and highlights the importance of local plant resources in addressing mining-related pollution.

5.4 Conclusions

This study assessed the phytoremediation potential of three aquatic plant species i.e., *Eichhornia crassipes*, *Lemna minor* and *Salvinia molesta* in treating acid mine wastewater collected from a gold mining site in Chanaka, Bindura. The findings revealed that all three species contributed to improvements in water quality, with *Eichhornia crassipes* demonstrating the highest efficiency across all parameters measured. It significantly increased the pH of the acidic wastewater, reduced turbidity, and removed substantial amounts of heavy metals (Pb, Cd, Fe, and Cu) and nutrients (nitrate and phosphate).

Lemna minor exhibited moderate performance, showing capacity for nutrient uptake and some metal removal, though less effectively than water hyacinth. *Salvinia molesta* was the least effective, struggling under acidic and metal-rich conditions, which affected both its growth and removal efficiency. While *Eichhornia crassipes* showed the highest average removal rates for most pollutants, statistical analysis using one-way ANOVA revealed that the differences in removal efficiency between the species were not statistically significant ($p > 0.05$) for any of the tested metals. This means that although water hyacinth appeared to perform better, the observed variation could not be confidently attributed to species-specific capabilities.

These results underscore the potential of phytoremediation as an affordable, sustainable, and environmentally friendly technique for remediating acid mine wastewater in Zimbabwe and similar regions. However, practical application requires consideration of factors such as ecological risk management, particularly for invasive species like water hyacinth, and safe disposal of contaminated biomass.

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Appendices

Appendix 1: Scientific classification of aquatic plants

Taxonomic rank	Water hyacinth	Duckweed	Salvinia
Kingdom	Plantae	Plantae	Plantae
Phylum	Tracheophyta	Magnoliophyta	Pteridophyta
Class	Liliopsida	Liliopsida	Polypodiopsida
Order	Commelinales	Arales	Salviniales
Family	Pontederiaceae	Araceae	Salviniaceae
Genus	*Eichhornia*	*Lemna*	*Salvinia*
Species	*Eichhornia crassipes*	*Lemna minor*	*Salvinia molesta*

Appendix 2: One-way ANOVA table for Lead removal

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-value	p-value
Between Groups	1.456	2	0.728	0.161	0.85186
Within Groups	189.976	42	4.523	—	—

Appendix 3: One-way ANOVA table for Cadmium removal

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-value	p-value
Between Groups	0.647	2	0.324	1.11	0.33888
Within Groups	12.237	42	0.291	—	—

Appendix 4: One-way ANOVA table for Iron removal

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-value	p-value
Between Groups	499.6	2	249.8	0.389	0.67997
Within Groups	26952.4	42	641.724	—	—

Appendix 5: One-way ANOVA table for copper removal

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-value	p-value
Between Groups	2.467	2	1.234	0.532	0.59131
Within Groups	97.377	42	2.319	—	—