

**POTENTIAL OF SELECTED PLANT SPECIES FOR PHYTOREMEDIATION OF
HEAVY METALS IN SOIL, AND WASTEWATER SEDIMENT FROM NAKIVUBO
WETLAND, UGANDA**

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DECLARATION

I **AKATUKUNDA ROSELYNE**, hereby declare that this dissertation titled "**POTENTIAL OF SELECTED PLANT SPECIES FOR PHYTOREMEDIATION OF HEAVY METALS IN SOIL, AND WASTEWATER SEDIMENT FROM NAKIVUBO WETLAND, UGANDA**" is authentic, original, and has never been submitted to any higher institution or university for an academic award.

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APPROVAL

We the undersigned verify that this dissertation entitled "**POTENTIAL OF SELECTED PLANT SPECIES FOR PHYTOREMEDIATION OF HEAVY METALS IN SOIL, AND WASTEWATER SEDIMENT FROM NAKIVUBO WETLAND, UGANDA**" was done by Akatukunda Roselyne, under our supervision and is ready for submission with our approval.

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DEDICATION

This dissertation is dedicated to my friends and family. I especially appreciate my devoted parents, Mr. Sam and Mrs. Rhoda Tumwesigye, whose support and insistence on perseverance have left a lasting impression on me. My siblings, Aggrey, Deborah, Israel, and Tophas, are incredibly dear to me and have never left my side.

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LIST OF ACRONYMS, ABBREVIATIONS AND SYMBOLS

AAS	Atomic Absorption Spectrometry
As	Arsenic
BAC	Biological Absorption Coefficient
BCF	Bio-concentration Factor/ Bio-coefficient Factor
Ca	Calcium
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Copper
Fe	Iron
HCl	Hydrochloric Acid
Hg	Mercury
HMs	Heavy Metals
HNO ₃	Nitric Acid
Mg	Magnesium
Mn	Manganese
Ni	Nickel
Op	Ornamental Plants
Pb	Lead
Pb ²⁺	Lead (II) ion
pH	Potential of Hydrogen
Sb	Antimony
TF	Translocation Factor
Zn	Zinc

ABSTRACT

Heavy metal pollution from industrial effluent has posed serious impacts on both humans and the environment. Several methods including chemical, biological, physical, and integrative approaches have been used to eliminate this kind of pollution. The study was conducted in Nakivubo wetland, Uganda, to assess the potential of phytoremediation as an eco-friendly and cost-effective method for removing heavy metals [Lead (Pb), Cadmium (Cd), Copper (Cu), and Arsenic (As)] from contaminated soil and wastewater sediments. Four plant species (*Commelina benghalensis*, *Pennisetum purpureum*, *Sida acuta*, and *Cynodon dactylon*) were analysed for their metal accumulation efficiency. Soil and wastewater sediment samples from four sites were analysed using Atomic Absorption Spectrophotometry (AAS). Results showed significant contamination, with Pb (4.66 - 83.49 mg/kg), Cd (0.65 - 1.49 mg/kg), Cu (5.64 - 52.09 mg/kg), and trace amounts of As (0.00 - 1.24 mg/kg) in soil, while wastewater sediments contained Pb (52.33 - 90.49 mg/kg), Cd (0.96 - 1.24 mg/kg), Cu (26.29 - 47.59 mg/kg), and As (0.08 - 0.28 mg/kg). All selected plant species effectively accumulated heavy metals. From soil, *C. benghalensis* was most efficient at accumulating Pb (39.82%) and Cd (171.3%), while *C. dactylon* was most effective for Cu (155.17%) and As (50.30%). In wastewater sediments, *C. dactylon* exhibited the highest Cu (137.51%) and As (116.83%) uptake, while *C. benghalensis* was most efficient for Pb (36.74%) and Cd (225.48%). High percentages of heavy metals in specific plants could have accumulated over time. Statistical analysis ($p < 0.05$) confirmed significant differences in metal accumulation. The Bio-concentration Factor, Translocation Factor, and Biological Absorption Coefficient values >1 indicated successful heavy metal uptake. *C. benghalensis*, *P. purpureum*, *S. acuta*, and *C. dactylon* are therefore effective phytoremediators and can be utilised for heavy metal cleanup in soil and wetlands.

CHAPTER ONE: INTRODUCTION

1.1 Background to the study

Globally, wastewater treatment has long been a critical research area due to increasing environmental awareness and the need to comply with stringent environmental regulations. Clean water is fundamental to economic prosperity in any country (Obaideen *et al.*, 2022). However, wastewater residues and sludge are often classified as hazardous materials, necessitating intensive treatment efforts (Zhang *et al.*, 2017). Industrial effluents typically contain a wide array of inorganic compounds, many of which are toxic, carcinogenic, or mutagenic, posing serious risks to both human and ecological health (Madhav *et al.*, 2020). These pollutants include pharmaceutical drugs, hydrocarbon fuels, radioactive materials, sewage, agricultural and industrial chemicals, and biological agents such as bacteria, viruses, and parasites (Singh *et al.*, 2022). Once released into the environment, such contaminants can accumulate in living organisms and disrupt entire ecosystems and food chains (Bashir *et al.*, 2020), underlining the urgent need for effective treatment of industrial effluents and contaminated soils. Therefore, wastewater is of great concern due to the contaminants it carries.

Among the chemical pollutants of great concern are heavy metals (HMs) and these are non-biodegradable and toxic in nature with densities greater than 5 g/cm³ (Mishra *et al.*, 2019; Ntwampe & Moothi, 2018). Heavy metals such as Lead (Pb), Copper (Cu), Mercury (Hg), Arsenic (As), Cadmium (Cd), and Zinc (Zn) occur both naturally and as a result of human activities including mining, manufacturing, and agriculture (Jagaba *et al.*, 2024). While trace amounts of some metals are beneficial to health, excessive exposure can be acutely or chronically toxic (Singh *et al.*, 2012). These metals are frequently discharged into the environment through industrial operations such as tanneries, electroplating, dyeing, mining, pulp and paper production, and battery manufacturing

(Tangahu *et al.*, 2011). Consequently, industrial effluents often contain elevated concentrations of Pb, Cd, Cr, Ni, Zn, and As (Shrestha *et al.*, 2021), which pose grave environmental and public health threats (Kabenge *et al.*, 2017; Bobade & Eshtiagi, 2015). Pollution from heavy metals occurs both through the direct dispersal of contaminated sewage sludge and via leaching or airborne movement into uncontaminated areas (Sedibe *et al.*, 2017). As such, HMs in excessive concentration become toxic and bioaccumulative and can persist in the environment.

In Uganda, despite the nation's rich water and soil resources, increasing industrial activity spurred by government efforts to boost economic output has intensified pollution risks (Kabenge *et al.*, 2017; Mbabazi *et al.*, 2021). In Kampala, rapid urbanisation and population growth have led to an upsurge in untreated sewage discharge into Lake Victoria through the Nakivubo channel, the city's primary drainage route (Bulonza, 2015; Nel, 2018). A study of waste management practices in the Lake Victoria basin found that many factories lacked waste treatment infrastructure (Walakira & Okot-Okumu, 2011), contributing to severe contamination. For instance, Pb concentrations in Nakivubo wetland soil reached 132.7 mg/kg, while water samples recorded Fe at 21.5 mg/L, Cu at 3.3 mg/L, and Cd at 0.14 mg/L (Nabulo *et al.*, 2008). Crops such as yams and sugarcane grown in these areas have accumulated Cd and Cr beyond safe limits, presenting health risks to consumers (Fuhrmann *et al.*, 2015). Similarly, sediment samples from Port Bell in Lake Victoria contained Cu levels between 6.111–7.111 mg/kg and Pb concentrations of 40.222–44.212 mg/kg, further illustrating the severity of metal contamination (Baguma *et al.*, 2022). In summary, discharge of untreated sewage water into water bodies may lead to increase in concentration of heavy metals and their bioaccumulation in living tissues.

Various waste treatment methods exist, including chemical and thermal approaches, but these are expensive, technologically complex, and environmentally taxing. Many generate large volumes of sludge and risk degrading essential soil properties (Li *et al.*, 2019). This has led to increased interest in sustainable and cost-effective alternatives like phytoremediation; a green technology that employs specific plants to extract, stabilise, or degrade harmful substances in contaminated environments (Tangahu *et al.*, 2011; Wani *et al.*, 2023). Waste water treatment leads to the removal of contaminants from water, making it safe for reuse or discharge into the environment.

Phytoremediation is not only environmentally friendly but also economically viable. It can effectively address a range of pollutants, including heavy metals, pesticides, hydrocarbons, and explosives. Plants utilise strategies such as avoidance to limit heavy metal uptake, and tolerance to neutralise metal toxicity when absorbed (Sekabira *et al.*, 2011; Sabreena *et al.*, 2022). While many plant species demonstrate the potential for HM remediation, annuals may be particularly useful as they sequester metals temporarily in their shoots, reducing long-term ecological risks (Sharma & Pandey, 2014). Effective implementation depends on selecting species with high biomass, adaptability to local conditions, and resilience to pollutant toxicity (Ashraf *et al.*, 2019). However, despite extensive global research, limited data exist on the performance of local plant species in Uganda's specific ecological context (Rezania *et al.*, 2016). Phytoremediation, therefore leads to treating wastes by using plants and is low cost and ecofriendly.

To address the wastewater challenge, the present study evaluated the phytoremediation potential of four native Ugandan plants: Wandering Jew (*Commelina benghalensis*), Napier grass (*Pennisetum purpureum*), Common wireweed (*Sida acuta*), and Scutch grass (*Cynodon dactylon*) in removing Pb, Cd, Cu, and As from contaminated soils and wastewater sediments in Nakivubo wetland, considering their adaptability to the local climate and ecological conditions

1.2 Statement of the problem

Industrial activities in Kampala have contributed to the contamination of soil and water bodies, particularly the Nakivubo channel and Lake Victoria, with hazardous heavy metals such as Pb, Cd, Cu, and As. These pollutants pose serious threats to both environmental and public health (Tangahu *et al.*, 2011). Although conventional remediation methods exist, they are often costly and environmentally damaging, making phytoremediation a promising alternative due to its sustainability and affordability. However, there is limited research on the use of native Ugandan plant species for environmental cleanup (phytoremediation) of heavy metals from Nakivubo wetland, hence the current study.

1.3 Justification for the study

With Kampala's rapid population growth and industrialisation, Uganda faces increasing industrial and municipal waste pollution, particularly in Lake Victoria through the Nakivubo wetland. Many factories lack proper waste treatment facilities (Walakira & Okot-Okumu, 2011), leading to the discharge of untreated effluents containing hazardous heavy metals. This contamination threatens water quality, soil health, and biodiversity. Phytoremediation offers an eco-friendly and cost-effective solution since it utilises the plants' adaptability to the local climatic conditions in the wetland. for removing heavy metals from polluted environments including chemical, biological, physical, and integrative approaches. While macrophytes like water hyacinth and duckweed have been used in other regions, the potential of native Ugandan plant species remains largely unexplored (Balamoorthy *et al.*, 2022).

The findings will contribute to environmental conservation efforts and align with Sustainable Development Goals (SDGs) 6, 14, and 15 by promoting access to clean water and sanitation (Unicef,

& Unicef, 2016), protecting aquatic ecosystems, and conserving terrestrial biodiversity (Katila *et al.*, 2019).

1.4 Objectives

1.4.1 General objective

To assess the potential of phytoremediation using *Commelina bengalensis*, *Pennisetum purpureum*, *Sida acuta* and *Cynodon dactylon* to remove Lead Cadmium, Copper and Arsenic from soil and wastewater sediments in Nakivubo channel / wetland.

1.4.2 Specific objectives

- i. To determine the ability of *Commelina benghalensis*, *Pennisetum purpureum*, *Sida acuta*, and *Cynodon dactylon* to absorb and accumulate the selected heavy metals from contaminated soils in Nakivubo channel/wetland.
- ii. To evaluate the ability of *Commelina benghalensis*, *Pennisetum purpureum*, *Sida acuta* , and *Cynodon dactylon* to absorb and accumulate the selected heavy metals from wastewater sediments in Nakivubo channel/wetland.
- iii. To examine the phytoremediation mechanism by which *Commelina benghalensis*, *Pennisetum purpureum*, *Sida acuta* and *Cynodon dactylon* remediate selected heavy metals from contaminated soil and wastewater sediments.

1.5 Null hypotheses

- i). *Commelina benghalensis*, *Pennisetum purpureum*, *Sida acuta*, and *Cynodon dactylon* cannot absorb and accumulate the selected heavy metals from contaminated soils in the Nakivubo wetland.
- ii). *Commelina benghalensis*, *Pennisetum purpureum*, *Sida acuta* , and *Cynodon dactylon* cannot absorb and accumulate the selected heavy metals from wastewater sediments in the Nakivubo wetland.
- iii). *Commelina benghalensis*, *Pennisetum purpureum*, *Sida acuta* , and *Cynodon dactylon* can neither remediate the selected heavy metals from contaminated soil and wastewater sediments by phytostabilisation nor by phytoextraction.

1.6 Scope of the study

The study was done in the Nakivubo wetland in Uganda. Soil, wastewater sediments and plant samples were collected from four sites (1, 2, 3 and 4) along the Nakivubo Channel and wetland. After the laboratory analysis, data analysis followed. The four plant species' (*Commelina benghalensis*, *Pennisetum purpureum*, *Sida acuta* , and *Cynodon dactylon*) capacities to accumulate Pb, Cd, Cu, and As from soil and wastewater sediments were then assessed in milligrams per kilogram. To determine the extent to which the heavy metals were accumulated in the plant parts (roots and shoots) from soil and wastewater sediments, the Bio-concentration factor (BCF), Biological Accumulation Coefficient (BAC) and Translocation factor (TF) were calculated and the mechanisms by which the plants took up the heavy metals identified. The study was done from June to December, 2023.

CHAPTER TWO: LITERATURE REVIEW

2.1 General overview

Most water systems, whether from industrial or residential sources, contain significant concentrations of heavy metals, posing serious environmental and health risks (Bhutiani *et al.*, 2016). To enable the reuse of wastewater for domestic or agricultural irrigation, the removal of these heavy metals is essential (Oyaro *et al.*, 2012). Traditionally, physical and chemical treatment methods have been widely employed globally to manage industrial waste (Artiola, 2019; Awuchi *et al.*, 2020). However, their widespread application can be limited by the high costs and the need for specialised equipment. In response to these limitations, the scientific community has shown increasing interest in using plants, particularly wetland species, for the remediation of mining and industrial waste. Wetland plants are therefore scientifically valued for their rapid uptake of heavy metals and trace elements, making them crucial agents in phytoremediation strategies (Saleh *et al.*, 2019; Yan *et al.*, 2022). In this research study area, Nakivubo Wetland may be a major receptor of municipal and industrial wastewater, stormwater runoff, and solid waste, which contain significant amounts of heavy metals.

2.2 Health effects of heavy metals

Over the past three decades, the accumulation of hazardous compounds in soils has increased substantially, posing serious threats to both ecosystems and human health (Azhar *et al.*, 2022). Plants growing in contaminated soils absorb elevated levels of heavy metals, which can enter the food chain and pose significant health risks to humans. Excessive Lead (Pb) exposure, for instance, is associated with kidney and brain damage, anaemia, and developmental issues in unborn children due to its ability to cross the placental barrier (Caserta *et al.*, 2013). Similarly, Cadmium (Cd)

contamination is linked to cancer, anosmia, neurological disorders, renal failure, skeletal deformities, and reproductive toxicity in males (Zhang & Reynolds, 2019), while Copper (Cu) and other heavy metals can impair liver and kidney function, cause gastrointestinal distress, hemolysis, and affect the respiratory tract (Karim, 2018). Generally, heavy metal contaminated soils through the food web can be of a negative impact to the human health.

In plants, heavy metal exposure particularly to Pb, Cd, and Cu leads to morphological abnormalities and oxidative stress (Rizvi & Khan, 2017). Elevated Pb levels can induce lignification in cortical parenchyma and irregular thickening of endodermis cell walls (Kaur *et al.*, 2014). Exposure pathways are not limited to soil alone; humans can also be affected through sediments and water sources contaminated with heavy metals (Singh *et al.*, 2022). Arsenic (As), for example, is typically encountered via inhalation of polluted air or ingestion of tainted food and water. Chronic exposure to As has been linked to hyperpigmentation, keratosis, vascular diseases, and various cancers (Rehman *et al.*, 2021; Chung *et al.*, 2014). With different heavy metal exposure pathways within the environment, there is a high risk of chronic exposure to these metals and later health impacts on living organisms in the ecosystem.

In light of these health risks, the World Health Organisation (WHO) has set stringent permissible limits for heavy metal concentrations in soil, plants, and drinking water. For example, the allowable limits for Lead are 85 mg/kg in soil and 2 mg/kg in plants; for Cadmium, 0.8 mg/kg in soil and 0.02 mg/kg in plants; for Copper, 36 mg/kg in soil and 10 mg/kg in plants; and for Arsenic, 20 mg/kg in soil and 0.05 mg/kg in plants. In drinking water, acceptable concentrations are: Hg – 0.001 mg/L, Pb – 0.01 mg/L, As – 0.01 mg/L, Cu – 2.0 mg/L, Cd – 0.003 mg/L, and Zn – 3.0 mg/L (WHO, 1996). These regulatory thresholds are designed to mitigate the toxicological effects of heavy metal exposure and protect public health.

2.3 Sources of heavy metals

Heavy metals are defined as elements with a density greater than 5 g/cm³. Due to their non-biodegradable nature and toxicity even at trace levels, they are inherently toxic and pose severe environmental and public health risks (Kabenge *et al.*, 2017; Singh *et al.*, 2012). Although many of these metals occur naturally in the Earth's crust, their environmental prevalence has escalated dramatically as a result of human activities such as industrialisation, mining, agriculture, and urbanisation (Wang *et al.*, 2014). Soils and vegetation are particularly vulnerable to contamination. Lead (Pb), for instance, accumulates in soil through industrial emissions, vehicular exhaust, and atmospheric deposition. While organic matter may partially mitigate Pb toxicity, elevated concentrations of Pb²⁺ remain highly detrimental to human health (Ayinde *et al.*, 2020; Tangahu *et al.*, 2011). Most of the heavy metals that negatively impact ecosystems, biodiversity and natural resources result from anthropogenic activities.

Cadmium (Cd), a soft, silver-white metal found in rock and soil formations, is primarily introduced into the environment through anthropogenic sources such as pigments, nickel-cadmium batteries, solder alloys, and plastic stabilisers (Khatun *et al.*, 2022). Industrial activities like smelting are major contributors to airborne Cd emissions (Elinder *et al.*, 2019). Copper (Cu), too, enters the soil through various human practices and can become incorporated into the food chain, thereby impacting ecosystems (Poggere *et al.*, 2023). Arsenic (As), another widespread contaminant, is frequently found in soil, groundwater, and sediments. Despite the use of Arsenic in agriculture, industry, and medicine for its germicidal and decay-resistant properties, its environmental persistence makes remediation particularly difficult (Shrivastava *et al.*, 2015; Chung *et al.*, 2014).

These heavy metals do not only affect terrestrial systems; they are also major pollutants in aquatic environments. They often enter water bodies via wastewater sediments from industrial effluents, sewage treatment plants, and urban runoff (Ali *et al.*, 2020). For example, Copper pollution in wastewater has been linked to industrial operations such as electroplating, dye and fertiliser production, mining, and metallurgy (Varma *et al.*, 2018). Urban infrastructure contributes further to this kind of pollution. Garages using Lead-accumulator systems discharge harmful waste into drainage networks, thereby contaminating surface waters (Masime, 2022). In Kampala, industrial establishments bordering the Nakivubo wetland release wastewater containing substantial heavy metal concentrations, significantly exacerbating local pollution (Kabenge *et al.*, 2017). Water sources pollution is majorly attributed to the industrial operations and discharged wastes from industrial areas.

In response to these challenges, some plant species have shown remarkable phytoremediation potential. For example, *Thlaspi (Noccaea) caerulescens* is capable of accumulating heavy metals such as Lead, offering a promising biological approach for environmental cleanup. These findings highlight the urgency of identifying primary contamination sources including batteries, metal piping, and residues from agrochemical and paint industries as a critical step toward mitigation (Mohtadi, 2014; Singh *et al.*, 2012). Depending on the source of contamination in a given environment, different plant species remediate heavy metals better than others.

2.4 Relevant theory on Phytoremediation technology and mechanisms

Remedial measures in polluted areas have focused on the solid-phase sources of metals, such as waste, contaminated soils, debris, or sludge (Azhar *et al.*, 2022). Knowledge about phytoremediation technology is crucial to maximise the effectiveness of trace elements removal by wetlands (Abbood *et al.*, 2024). In this context, soil microorganisms are employed to reduce or eliminate hazardous

organic and inorganic contaminants from the environment (Mocek-Płóćiniak *et al.*, 2023). Key phytoremediation approaches include phytostabilisation, rhizofiltration, phytoextraction, phytoaccumulation, and phytovolatilization (Yan *et al.*, 2020; Park & Oh, 2023; Hu *et al.*, 2024). These approaches are used to examine the extent to which contaminants are accumulated within any plant selected for phytoremediation.

Phytoremediation is an economical and environmentally friendly method that utilises plants to purify contaminated areas, including soil, water, and sediments (Bhat *et al.*, 2022). This technology can manage heavy metals, oil, explosives, and pesticides (Asante-Badu *et al.*, 2020), relying on plant strategies of avoidance and tolerance to handle heavy metal presence (Sekabira *et al.*, 2011). Phytostabilisation and phytoextraction are the commonly used phytoremediation approaches when using wetland plants. In phytostabilisation, heavy metals are accumulated through root hairs and adsorbed onto root surfaces, whereas phytoextraction involves the transport of these metals to aerial plant parts (Shackira *et al.*, 2019). The effectiveness of phytoremediation depends on plant species, their ability to accumulate or stabilise contaminants, and environmental conditions (Sharma *et al.*, 2023).

Studies show that different plant parts accumulate heavy metals at varying rates, with roots often absorbing more than shoots (Tupan & Azrianingsih, 2016). Through evapotranspiration, plants absorb soil nutrients and contaminants, facilitating their movement from roots to shoots and enabling eventual removal while preserving soil integrity (Alam, 2017; Tarish *et al.*, 2024). Hyperaccumulator species, characterised by high shoot-to-root metal concentration ratios (TF >1), are efficient in absorbing and storing heavy metals (Garba *et al.*, 2018). These plants exhibit rapid growth, high biomass, and detoxification capabilities (Ramana *et al.*, 2021; Tangahu *et al.*, 2011), and are preferred for their ability to thrive in toxic conditions with minimal maintenance.

Effective phytoremediation requires high plant heavy metal concentrations, bio-concentration factors (BCF), and translocation factors (TF) (Hryniewicz *et al.*, 2018; Li *et al.*, 2023). Native plants are often favoured over exotic species due to their resilience in nutrient-poor and arid soils (Ranjan *et al.*, 2015; Mayonde, 2018). Phytoextraction of Lead (Pb) has been widely studied, with commercially viable phytoremediators being those capable of accumulating over 1% Pb in their shoots (Cunningham & Berti, 2020). Other techniques, including phytostabilisation, rhizofiltration, phytoaccumulation, and phytovolatilisation, also contribute to remediation efforts (Wani *et al.*, 2023). Selecting the right plant species, based on metal concentrations in tissues, accumulation rates, and plant density, is vital for successful phytoremediation.

Certain herbaceous plants, such as *Bidens pilosa* and *Lantana philippensis*, have been identified as Pb hyperaccumulators with shoot concentrations exceeding 1000 mg/kg, while *Typha latifolia* and *Mimosa pudica* act as effective Pb stabilisers in the rhizosphere with BCF=1 (Yongpisanphop *et al.*, 2017; Guo *et al.*, 2013). Additional research highlights *Miscanthus sinensis* and *Imperata cylindrica* for Cadmium (Cd) and Mercury (Hg) phytoextraction, *Persea americana* for Cd and Pb stabilisation, and *Cynodon dactylon* for Arsenic (As) and Antimony (Sb) stabilisation (Xue *et al.*, 2014). In serpentine soils, *Alyssum bracteatum*, native to Iran, was recognised as a superior nickel (Ni) hyperaccumulator (Ghaderian *et al.*, 2015). Hyperaccumulator plants accumulate extremely high concentrations of heavy metals in their tissues. They can thrive in soils or water that would be toxic to other plants.

Woody biomass has also proven effective in phytoremediation. *Populus* and *Salix* species exhibit root systems that function as sinks for trace elements, supporting phytostabilisation and Arsenic immobilisation (Vamerali *et al.*, 2014). Ornamental plants like *Nicotiana glauca*, *Petunia hybrida*, *Lepidium sativum*, and *Lolium perenne* offer aesthetic value while enhancing soil conditions (Khan

et al., 2021). Continued studies on hyperaccumulators from the *Euphorbiaceae*, *Fabaceae*, *Violaceae*, and *Brassicaceae* families, particularly *Brassicaceae* species, show strong capabilities for Pb, Cd, Zn, and Ni removal (Ufimtseva, 2015). The physiological mechanisms of phytoremediation, such as osmoregulation, dispersion, occlusion, translocation, and accumulation, have also been reviewed (Khan, 2020). The physiology of selected plants matter in the process of phytoremediation.

Wetland plants like *Ludwigia stolonifera* have shown a remarkable capacity to remove Pb, Cd, and Cr from wastewater, achieving up to 99% removal within four days (Saleh *et al.*, 2019). *Pistia stratiotes*, with its expansive root system, is effective at accumulating Pb, while constructed wetlands with diverse flora report Pb and Cd removal rates of 99.28% and 65.89%, respectively, at neutral pH (Singh *et al.*, 2012). Coastal and wetland species are also noted for stabilising heavy metals in sediments and functioning as bio-indicators due to their high root metal concentrations (Yan *et al.*, 2022; Bonanno & Cirelli, 2017). However, plant responses to metal uptake are highly species-specific and sometimes unpredictable due to other present factors at the time of metal absorption and accumulation.

The effectiveness of wetland phytoremediation is evident from studies in Africa. In Nairobi, Kenya, wastewater and soil samples showed elevated soil heavy metal levels compared to wastewater (Kinuthia *et al.*, 2020). Aquatic phytoremediation requires plants that can accumulate toxins in aerial parts and survive in aquatic habitats (Eid *et al.*, 2020). Macrophytes such as *Water mimosa*, *Water hyacinth*, *Water spinach*, *Smartweed*, and *Lesser duckweed* are popular in wastewater treatment. The aquatic plants are suitable for phytoremediation because of their fast growth and pollutant retention (Balamoorthy *et al.*, 2022).

Sewage sludge-grown plants like *Alternanthera philoxeroides*, *Amaranthus spinosus*, and *Amaranthus sessilis* are effective at heavy metal accumulation, though their use for food poses health risks due to bioaccumulation (Sabreena *et al.*, 2022). Urban wetlands host plants such as *Commelina benghalensis* and *Cynodon dactylon*, which have been recognised for their heavy metal remediation potential (Sekabira *et al.*, 2011). Advances in rhizofiltration, including blastofiltration using seedlings, are promising for wastewater metal removal (Sabreena *et al.*, 2022). Ongoing research aims to improve phytoremediation techniques through enhanced field application and hyperaccumulator efficiency (Chaney *et al.*, 2020).

In Uganda's Lake Victoria basin, poor waste treatment infrastructure among factories contributes to pollution (Walakira & Okot-Okumu, 2011). Heavy metal assessments in Nakivubo Wetland revealed significant Fe, Cu, Cd, and Pb levels in water, soil, and edible plants (Fuhrimann *et al.*, 2015), underlining the need for urgent phytoremediation interventions. While some terrestrial plants are effective metal accumulators, aquatic and wetland plants have demonstrated superior efficiency in removing metals from wastewater (Rezania *et al.*, 2016). Overall, phytoremediation remains a cost-effective and sustainable solution for mitigating heavy metal contamination in both terrestrial and aquatic ecosystems.

2.5 Summary of literature and research gaps

Phytoremediation can be implemented through both *in-situ* and *ex-situ* techniques (Kabenge *et al.*, 2017). Among these, the *in-situ* applications are more commonly employed due to their ability to reduce the spread of pollutants in soil, water, and air, thereby mitigating immediate environmental risks (Liu *et al.*, 2024). An additional benefit of the *in-situ* approach is its capacity to address multiple contaminants simultaneously without requiring a disposal site (Kuppusamy *et al.*, 2016).

However, effective implementation of *in-situ* applications necessitates evaluating various soil factors, such as erosion and leaching that can influence pollutant mobility and treatment efficacy.

Ex-situ bioremediation techniques, on the other hand, are governed by specific criteria including the geographic location of the contaminated site, the cost of treatment, the type and extent of pollution, and the nature of the pollutants involved (Kumar *et al.*, 2018). While *ex-situ* methods typically incur higher costs compared to *in-situ* alternatives, they offer better control, easier management, and can be applied to a broader range of soil contaminants (Sabreena *et al.*, 2022). The two techniques differ significantly in terms of experimental control and consistency of treatment outcomes (Shiryaev *et al.*, 2024) with *ex-situ* methods offering better control.

Given the health risks associated with environmental contamination by toxic heavy metals, and the high cost and environmental burden of traditional remediation methods, there is growing interest in developing cost-effective and eco-friendly alternatives such as phytoremediation (Saleh *et al.*, 2019). Among heavy metals, Lead (Pb), Cadmium (Cd), and Chromium (Cr) are considered the most hazardous to ecosystems (Rahman & Singh, 2019). Expanding the use of phytoremediation systems requires in-depth research into the mechanisms by which these metals and other contaminants are absorbed, translocated, and accumulated by plants. To ensure successful implementation of phytoremediation on a larger scale, future research must also prioritise field-level applications that bridge the gap between laboratory findings and real-world conditions (Wang *et al.*, 2020; Huang *et al.*, 2020). There is limited research on the use of indigenous or local species in phytoremediation. Scanty data and information exist on the bioaccumulation factors (BAF) and translocation factors (TF) for plants native to wetlands like Nakivubo.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Study area

The study was carried out in Nakivubo Wetland along Nakivubo Channel. Nakivubo wetland is located at 00°18'N32°38'E elevation 1135 m above sea level. This wetland covers a total area of about 5.29 km² and has a total catchment of more than 40 km (Isunju & Kemp, 2016). Nakivubo channel crosses highly populated Kampala slums, agricultural fields, and industrial areas, which are potential sources of heavy metal-contaminated wastewater. To reduce the effects of floods, the primary purpose of this channel was to transport storm water from Kampala into Lake Victoria's Murchison Bay (Sekabira *et al.*, 2011). In this study, four sites in Nakivubo wetland were the sample collecting points for the selected four plant species (*Commelina benghalensis*, *Pennisetum purpureum*, *Sida acuta*, and *Cynodon dactylon*), soil, and wastewater sediment samples (Table 3.1 and Figure 3.1).

Table 3. 1 Sample site location

Site	Description/Nearby activities	GPS Coordinates
1	Mukwano discharge point (Mukwano factory and garage).	36 N 454442.00 m E 34557.00 m N
2	Industrial waste dumping site (Paint factories)	36 N 456890.00 m E 34399.00 m N
3	Murchison Bay waste discharge point	36 N 458997.00 m E 32965.00 m N
4	Control site (500 meters from the channel)	36 N 459382.00 m E 32997.00 m N

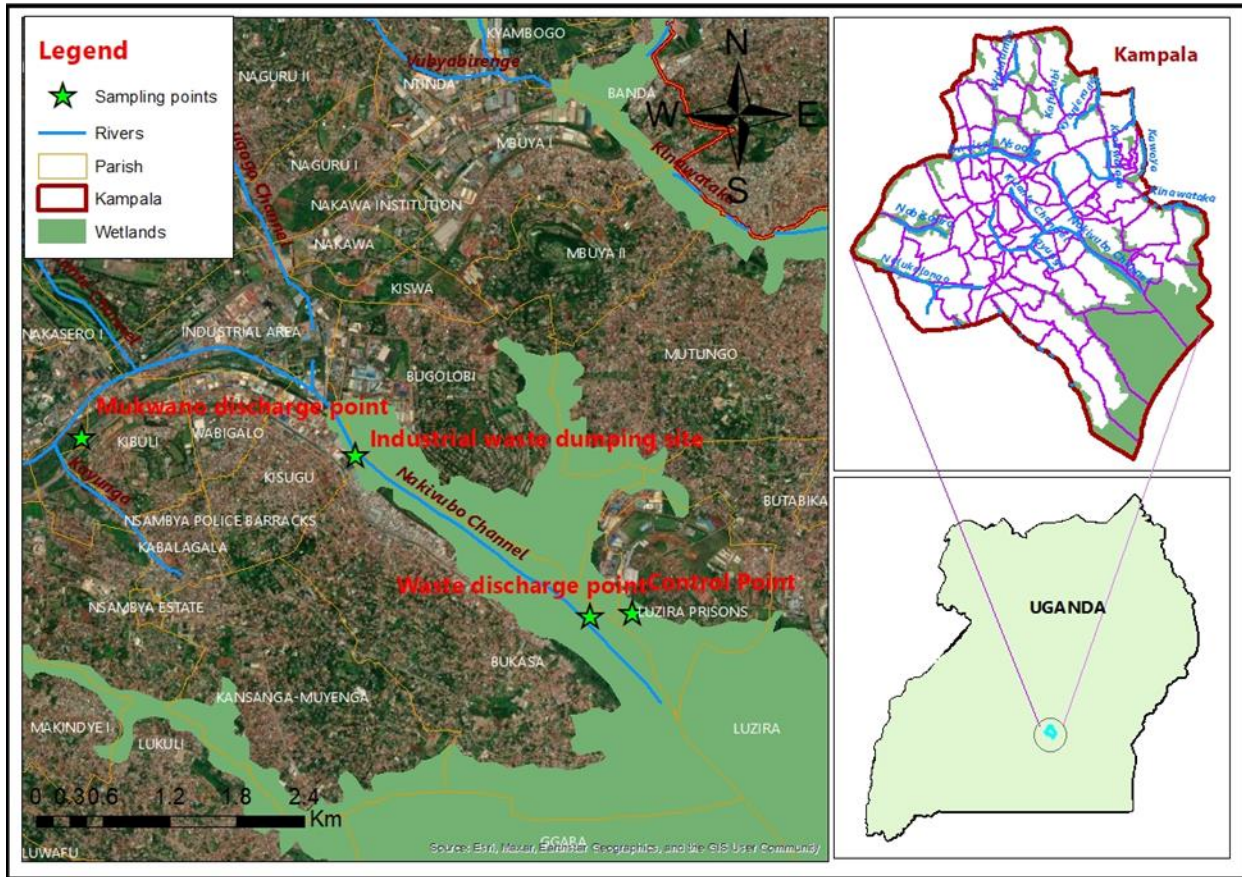


Figure 3. 1 The map showing research sampling sites in Nakivubo wetland, Uganda.

3.2 Research design

A cross-sectional study was conducted during the dry season (June-July, 2023) at four different sites (1, 2, 3 and 4) in Nakivubo wetland. Study sites 1, 2, and 3 were found in this wetland along the Nakivubo channel, not far away from industrial places within the city. Study site 4 was a control site for plants growing on soil. Considering the plants' availability both along the wastewater channel shore and their distance (0.5m) away on soil, their biomass and extensive fibrous and tap root systems; different samples of plant species (*Commelina benghalensis* , *Pennisetum purpureum*, *Sida acuta* and *Cynodon dactylon*) (Figure 3.2), soil and wastewater sediment were collected from the study sites. Additionally, the plants were well adapted to the local climate conditions along the

Nakivubo channel, making them ideal candidates for the investigation. The samples were later taken to the laboratory for heavy metal (Pb, Cd, Cu and As) analyses.

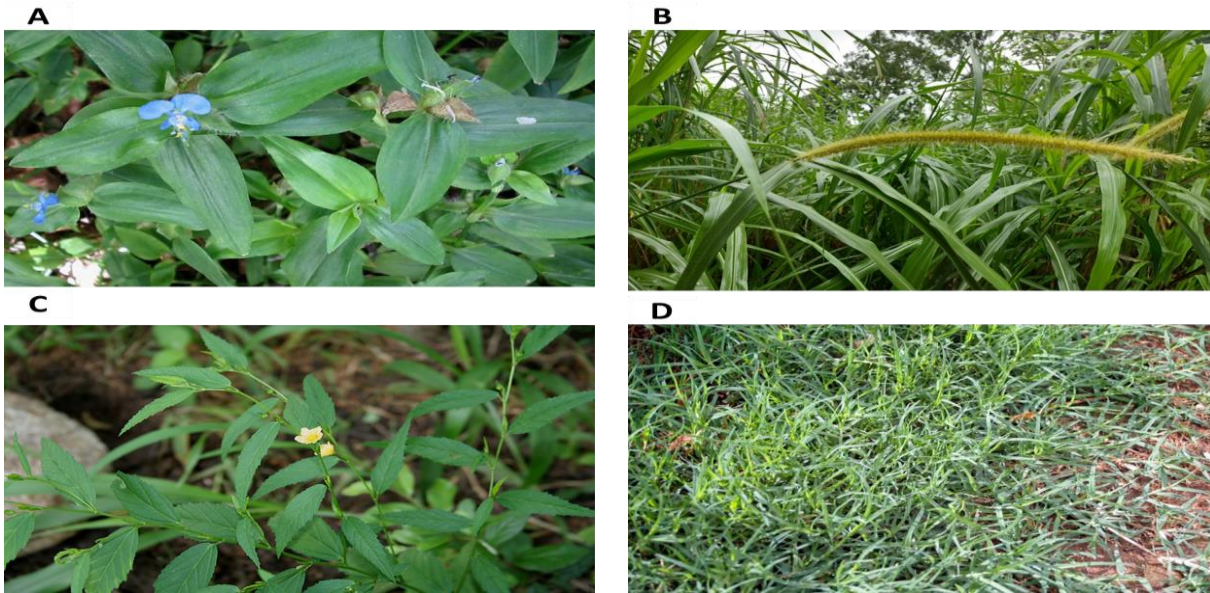


Figure 3. 2 The plant species evaluated for heavy metal reduction in Nakivubo wetland: (A) Wandering Jew (*Commelina benghalensis*), (B) Napier Grass (*Pennisetum purpureum*), (C) Common Wireweed (*Sida acuta*), and (D) Scutch Grass (*Cynodon dactylon*).

3.3 Sample size determination, sample collection, and material preparation

3.3.1 Soil sample size

By simple random sampling, 15 soil samples (3 samples from site 1 and $4 \times 3 = 12$ samples from sites 2, 3, and 4) were picked from where the respective plant species were growing - 0.5 m away from the channel shores (Metutera, 2022) for sites 1, 2, and 3 and 500m away from the channel for site 4 (control site). The sample size was determined after combining the original 3 - 4 soil samples from around the same plant species at each site into single composite samples (Li *et al.*, 2022).

3.3.2 Soil sample collection

Soil samples were randomly taken from each site in the vicinity of each plant species' root depth (5–10 cm) using a trowel and a soil auger. The equipment (trowel, auger) was thoroughly cleaned between samples with a liquid detergent and water, followed by a final rinse with deionised water (Le Stradic *et al.*, 2021). Soil samples from the same plant species location were then combined into a single composite sample (Sekabira *et al.*, 2011), placed in polythene bags (Appendix 5C) and transferred to the laboratory for further preparation and analysis.

3.3.3 Preparation of soil for heavy metal analysis

Soil samples were dried on clean wrapping paper at room temperature for 3 days. Later, 5g of dry soil were weighed into a 250 ml flask, 25 ml of concentrated HCl was added, and placed on a medium hot plate (Appendix 5F). After 15 minutes, 15 ml of concentrated HNO₃ was added. After a 20-minute digestion, 25 ml of concentrated hydrochloric acid and 25 ml of deionised water were then added. The sample was heated at 370 °C to dissolve all soluble salts and release the HNO₃ digestive gases. After cooling, the solution was diluted with 100 ml of cold deionised water. It was thoroughly mixed and then poured into 100 ml volumetric flasks using No.2 Whatman filter paper. It was later transferred to 50 ml standard flasks with screw cap fittings. The solution was ready for analysis of Pb, Cd, Cu, and As (Hu & Qi, 2014; Asher *et al.*, 2020).

3.3.4 Wastewater sediment sample size

The sample size was determined after combining the original 3 - 4 sediment samples from around the same plant species at each site into single composite samples (Li *et al.*, 2022). A total number of 11 samples of wastewater sediment (3 samples from site 1 and 4x2=8 samples from sites 2 and

3) were randomly picked from the 3 sites along the channel shores (Vallarino *et al.*, 2014) where the respective study plant species were growing (Appendix 5B).

3.3.5 Wastewater sediment sample collection

Wastewater sediment samples were randomly taken from each site. This was done at the location of each plant species' root depth along the shore using a trowel and a plastic container (Ofori *et al.*, 2022). The trowel was thoroughly cleaned between samples with a liquid detergent and water, followed by a final rinse with deionised water. Wastewater sediment samples from the same location in relation to plant species were combined into a single composite sample (Sekabira *et al.*, 2011), and the samples were placed in polythene bags and taken to the laboratory for additional preparation and analysis.

3.3.6 Preparation of wastewater sediment for heavy metal analysis

Wastewater sediment samples were dried on clean wrapping paper at room temperature for 3 days. They were then homogenised and dry milled in a ball mill (Mohiuddin *et al.*, 2011), resulting in a 2 mm fine powder (metals tend to adhere to fine particles) (Meier *et al.*, 2019). Later, 20 ml of aqua regia (HCl/HNO₃ 3:1) was used to digest 1.25 g of each sample in an open conical flask set on a hot plate (Appendix 5F). After boiling almost to dryness, the digest was cooled to room temperature. Then, 5.0 ml of hydrogen peroxide was gradually added to finish the digestion process, and the mixture was heated once more in a fume cupboard until it was almost dry. 10 ml of de-ionised water was used to wash the flask walls, and 5 ml of HCl was added, mixed, and heated for 5 minutes. After the digest had cooled down, it was transferred to a 50 ml standard flask and filled to the mark with de-ionised water, ready for analysis (Hu & Qi, 2014).

3.3.7 Plant sample size

Simple random sampling of each selected species of plants was applied at each site (Michalet *et al.*, 2024). At least 3 individuals of *Commelina benghalensis*, *Pennisetum purpureum*, *Sida acuta*, and *Cynodon dactylon* were collected from soil and wastewater sediment at each sampling site (Sekabira *et al.*, 2011). At site 1, only 3 plant species were found; here, *Pennisetum purpureum* was not found and so 45 plants (from soils) were collected from four sites ($12 \times 3 = 36$ plant samples from sites 2,3 and 4 plus $3 \times 3 = 9$ plants from site1) while 33 plants (from wastewater sediments) were collected from 3 sites ($12 \times 2 = 24$ plant samples from sites 2 and 3 plus $3 \times 3 = 9$ plants from site1). This gave a total number of 78 plant samples from both soil and wastewater sediment.

3.3.8 Plant sample collection

Plant sample collection along the channel shores and from the nearby soils was based on observed plant coverage at the sites and plant health (Cui *et al.*, 2009). A trowel was used to uproot each plant species. Water and a liquid detergent were used to clean the trowel between samples. The final rinse was done with deionised water (Le Stradic *et al.*, 2021). The plant samples were collected into polythene bags and later transferred to the laboratory for further preparation before the analyses.

All sample collection from the sites was done at the harvesting time in the dry months (Ibne Kamal, 2023) of June-July,2023, and more importantly, when photosynthesis in plants had reached its maximum.

3.3.9 Preparation of plant parts for heavy metal analysis

Plant samples were washed with running tap water to remove debris (Appendix 5D). Samples were separated into portions of roots and shoots (Sekabira *et al.*, 2011), and later divided into smaller pieces (Khan *et al.*, 2017). The samples were wrapped in aluminium foil and dried for 24 hours at 105°C in the laboratory oven dryer. They were then homogenised into fine grains using a blender and a 0.5mm sieve before the laboratory chemical tests of Pb, Cd, Cu, and As concentration in roots and shoots. 0.4 g of dried samples were measured using an analytical balance KERN ABJ-NM/ABS-N and transferred to 250 ml conical flasks (Appendix 5E). 7 ml of 65% HNO₃ was added, and the mixture was allowed to sit overnight before being heated on a hot plate. An open-vessel digestion was carried out for approximately 10 minutes at 300 °C on a hot plate (Appendix 5F) until the mixture was almost dry. After adding 5.0 ml of 30% hydrogen peroxide to finish the digestion, the liquid was heated once more until it was almost dry. The residues did not dissolve completely. After the digest liquor had cooled down, it was filtered through No.2 Whatman filter paper. It was then transferred into standard 25 ml flasks, and the appropriate amount of deionised water was added to the mark (Estefan *et al.*, 2013).

3.4 Study site selection

By observation, the study plants survived in significant numbers along the channel and in the wetland, where industrial waste materials (Appendix 5A) were suspected to be affecting both the soil and available water sources (Butt *et al.*, 2021). These plants were wild and native to the environment. The study aimed to assess the potential of selected plant species to remediate heavy metals (Pb, Cd, Cu, and As) from both soil and wastewater sediments at the selected sites. Since the study was conducted *in situ*, the source of heavy metals found in plants was either the soil or

sediments where the plants were growing. Any amounts of heavy metals found in plant tissues represented the maximum the plant could accumulate over time.

The study was conducted at four sites along the Nakivubo channel wetland. Sites 1, 2, and 3 were selected based on the flow of the channel through the industrial area, while site 4 served as a control site, located approximately 500 meters away from the wastewater channel. Site selection was influenced by the proximity of each location to the estimated sources of heavy metals (Rahman *et al.*, 2021), as the channel flows through an industrial zone. The four selected study plants were commonly found at least in two of the selected study sites near the estimated contaminant sources.

Site 1 was located approximately 300 meters from the Mukwano factory, where plants were observed growing along the channel near a local car washing bay and a garage adjacent to the factory. At site 2, plants thrived on soil about 0.5 meters from the channel bank, where small amounts of industrial waste had been dumped. At site 3, the plants survived in shallow wastewater flowing into the lake from the rest of the city. The control site, site 4, consisted of the same plant species growing on soil about 500 meters away from the contaminated channel (Figure 3.3).

The structure of the plants' roots and leaves was significant in this study. Deep-rooted plants and those with widespread leaves are ideal for phytoremediation studies (Pinhey & Tebbs, 2022), as these features enhance their ability to absorb contaminants. The dry season was selected for the study, as plants generally grow well during this time due to higher photosynthetic activity. During this period, phytoremediation is expected to be more active, especially as plants approach their harvest stage. On the other hand, increased evaporation in the dry season was anticipated to concentrate heavy metals in water bodies, leading to more accurate analytical results.

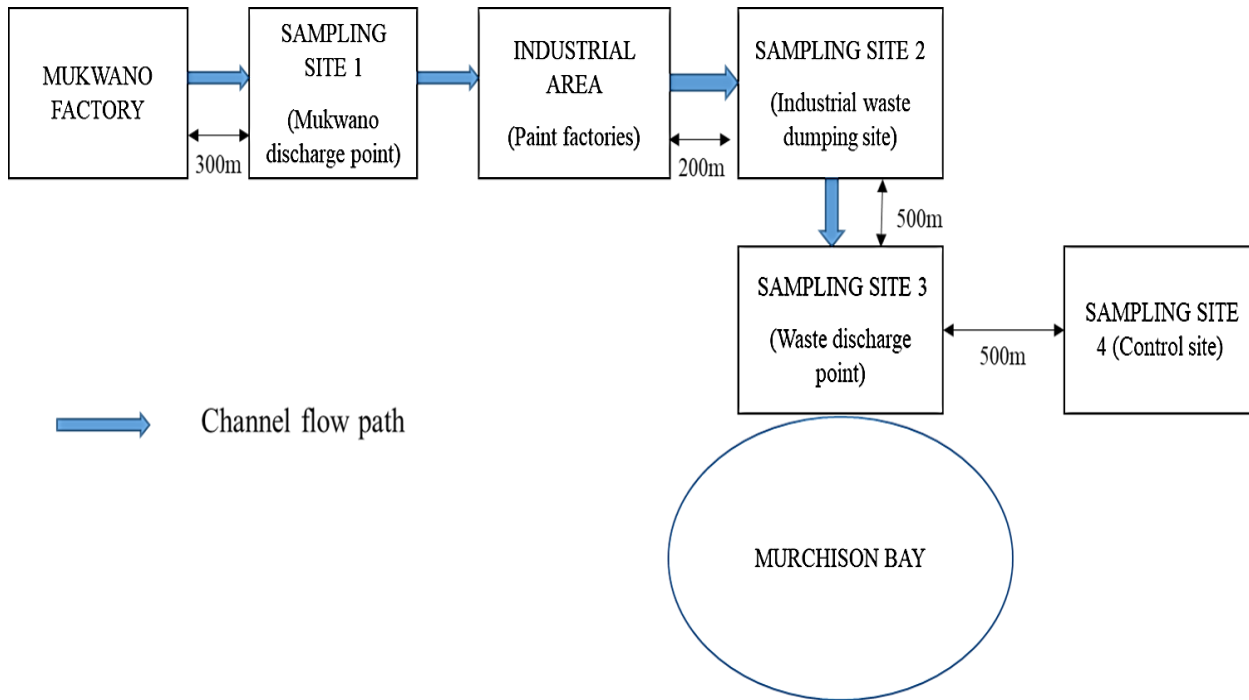


Figure 3. 3: Study sampling sites

3.5 Sample analysis

All analyses were done in the Chemistry laboratory at Uganda Industrial Research Institute, Nakawa (Appendix 5D-5F). Pb, Cd, Cu, and As concentrations were analysed by directly aspirating and atomising sample solutions of plant parts (roots & shoots), soil and wastewater sediments in a Perkin Elmer Analyst 400 atomic absorption spectrophotometer (AAS) (Kendir, 2013) (Appendix 3G). In AAS, analytes (Pb, Cd, Cu and As) were first atomised to release and record the characteristic wavelengths of the elements (Pb: 283.3 nm; Cd: 228.8 nm; Cu: 324.8 nm; As: 193.7 nm). When an atom absorbs a specific amount of energy, the electrons within that atom shift up one energy level during excitation. This energy is linked to a certain wavelength that characterises the element (Penner *et al.*, 2017). With AAS, the elements (Pb, Cd, Cu and As) could be identified and their concentrations calculated in milligrams per kilogram (mg/kg) depending on the light's wavelength and power.

3.6 Quality control

During the laboratory analyses of Pb, Cd, Cu, and As in all samples of soil, wastewater sediment, and plant parts, heavy metal digestion and measurement were done on dry, homogenised duplicate samples. Analytical-grade reagents and well-cleaned glassware were utilised. The instrument readings were adjusted using blank reagents (Omar *et al.*, 2015). Standard solutions with established Pb, Cd, Cu and As concentrations were used to calibrate the apparatus. Throughout the study, deionised water was used (Bhat *et al.*, 2022).

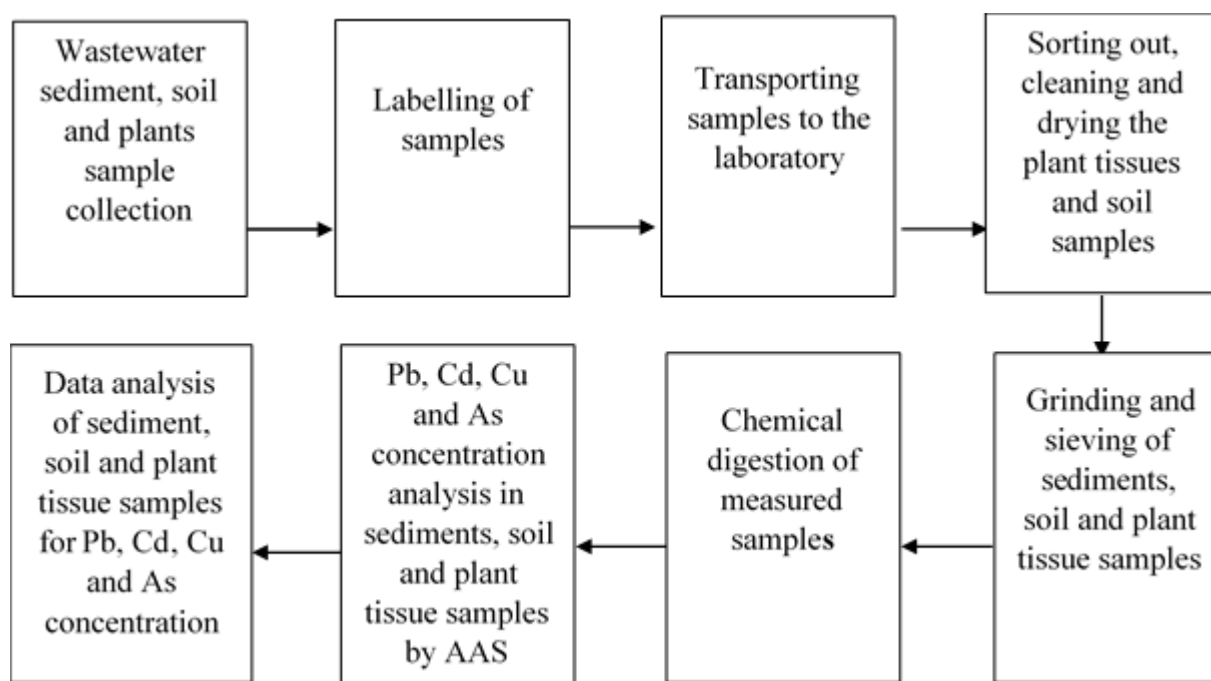


Figure 3. 4: Site sampling, material preparation and data collection flow chart

3.7 Data analysis

All the data were entered in Microsoft Excel version 2010 and analysed using GraphPad Prism Version 8.1. By computing the means and standard error of the heavy metal concentrations in each plant species, the test plants' phytoremediation efficiency for removing heavy metals from soils and wastewater sediments was determined. Analysis of Variance (Two-way ANOVA) was used to

compare the statistical analysis at a 95% confidence level and 5% margin of error. Tukey's multiple comparisons test was further done to specify which plant groups growing on both soil and wastewater sediments at different sites are significantly different from each other in concentrations of HMs (Zhang *et al.*, 2019). By computing TF, BCF, and BAC values, the mechanisms of phytoremediation among plants growing on both soil and sediments were identified (Naz *et al.*, 2022), and results were displayed in tables and figures.

3.8 Estimation of phytoremediation indices

According to Jeelani *et al.* (2017), the biological concentration factor (BCF) was computed as the ratio of the metal concentration in plant roots to the metal concentration in soil or wastewater sediments. The formula used was: $BCF = \text{Metal concentration in plant roots} / \text{Initial concentration of metal in substrate (soil/sediment)}$. This value indicates the plant root's capacity to accumulate a given metal relative to its concentration in the soil or sediment and is used to assess a plant's potential for phytostabilisation.

The translocation factor (TF) was calculated as the ratio of the concentration of heavy metals in the plant shoot (stem and leaves) to the concentration in the plant roots: $TF = \text{Metal concentration (shoot)} / \text{Metal concentration (roots)}$. This ratio reflects the plant's ability to transfer metals from its roots to its aerial parts and is used to evaluate phytoextraction capacity (Dinu *et al.*, 2020).

Additionally, the biological absorption coefficient (BAC) was determined by dividing the heavy metal content in plant shoots by the concentration of heavy metal in soil or wastewater sediments. A plant with a BAC value greater than one ($BAC > 1$) is considered effective for phytoextraction (Ng *et al.*, 2016). These three indices; BCF, TF, and BAC were essential for evaluating the phytoremediation potential of the selected plant species.

CHAPTER FOUR: RESULTS

4.1 Ability of selected plant species to absorb and accumulate Lead, Cadmium, Copper and Arsenic from contaminated soils

4.1.1 Heavy metal concentration in soil contamination at different sites

The results indicated that Lead, Cadmium, Copper, and Arsenic were present in all soil samples collected from the four different sites. Lead was the most prevalent heavy metal at site 1, with a mean concentration of 70.18 mg/kg, followed by Copper (52.09 mg/kg), Cadmium (1.15 mg/kg), and Arsenic (1.02 mg/kg). At site 2, Lead was the most abundant heavy metal with a concentration of 83.48 mg/kg, followed by Copper (34.67 mg/kg), Cadmium (1.26 mg/kg), and Arsenic (0.65 mg/kg). At site 3, Lead was the most abundant heavy metal (25.36 mg/kg), followed by Copper (24.31 mg/kg), Cadmium (1.49 mg/kg), and Arsenic (1.24 mg/kg). At site 4, Copper was the most abundant heavy metal (5.64 mg/kg), followed by Lead (4.66 mg/kg), Cadmium (0.65 mg/kg), while soil samples from the control site did not contain Arsenic (Figure 4.1). Heavy metals were detected in soil samples from all four sites, with varying concentrations. Lead was the most dominant metal at sites 1, 2, and 3, especially high at site 2, indicating possible heavy contamination. Copper was most prevalent at site 4, where Arsenic was notably absent.

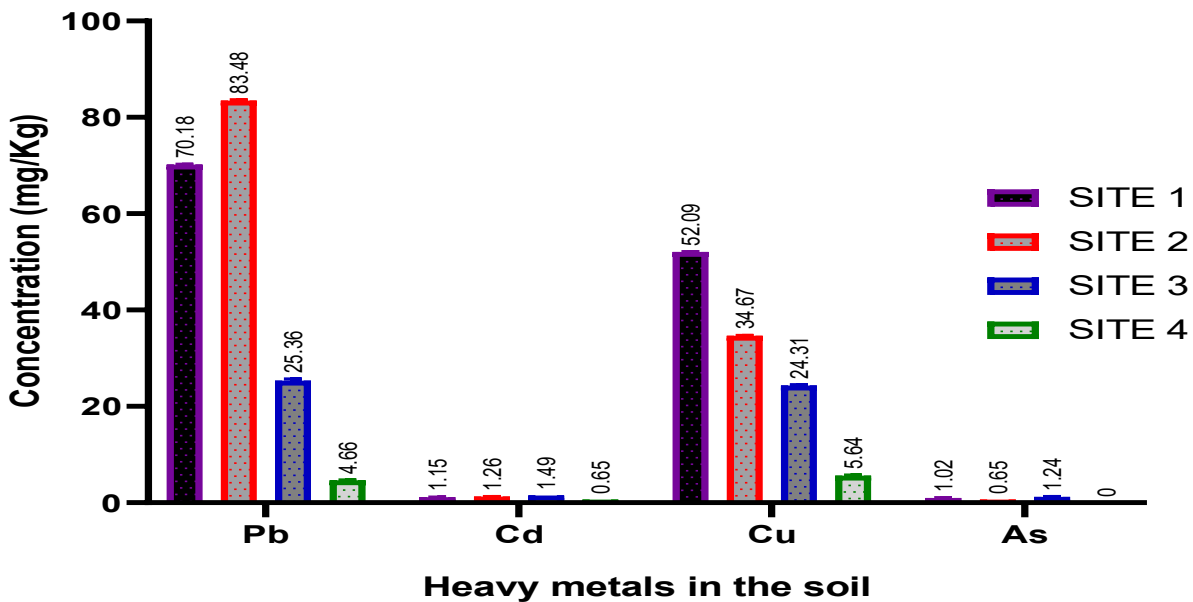


Figure 4. 1 Mean concentrations (mg/kg) of heavy metals in the soil at different sites

4.1.2 Heavy metal concentration in plant species growing in contaminated soil

4.1.2.1 Lead

All plant species demonstrated the ability to absorb Lead from the soil, regardless of location. *C. benghalensis* from sites 2 and 3 exhibited the highest Pb accumulation of all plants tested, with a concentration of 33.24 mg/kg and 16.49 mg/kg respectively. Similarly, *C. dactylon* from site 1 showed significant uptake (28.43 mg/kg). In contrast, site 4 (control site) consistently exhibited the lowest levels of Pb uptake across all species. For example, *C. dactylon* and *S. acuta* from site 4 absorbed only 1.17 mg/kg and 0.85 mg/kg of Pb respectively, while *C. benghalensis* and *P. purpureum* recorded low concentrations of 0.98 mg/kg and 1.25 mg/kg respectively. (Figure 4.2).

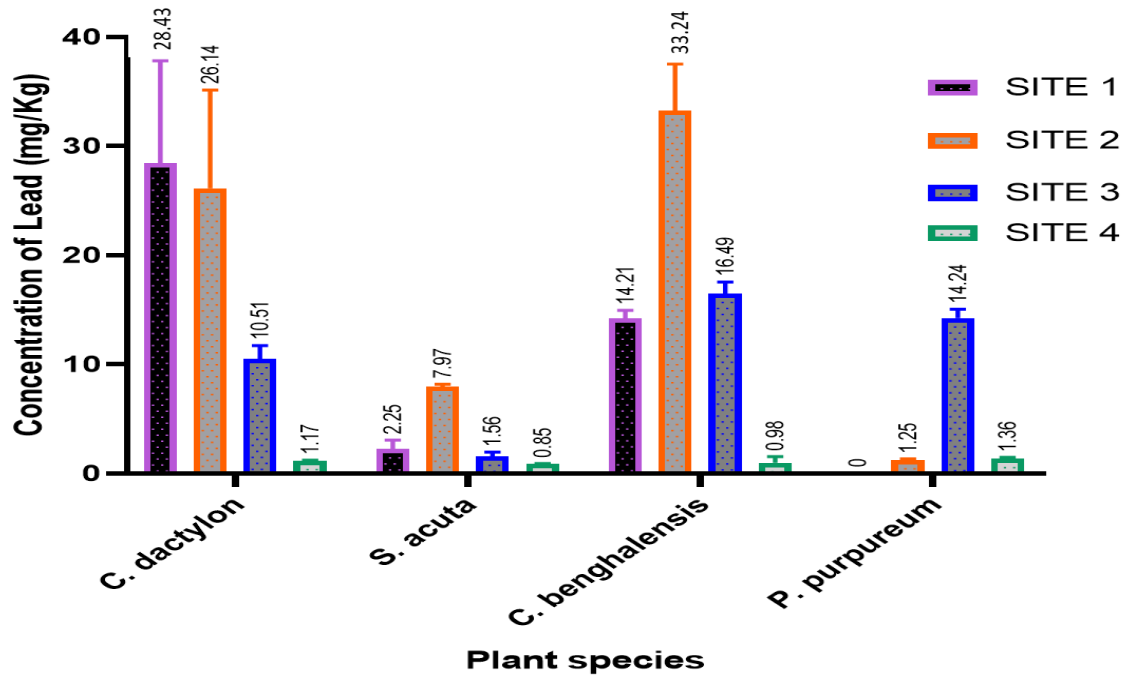


Figure 4. 2: Mean concentrations (mg/kg) of Lead in plant species growing on soil at different sites.

The mean concentrations of the Lead absorbed by the different plants at the different sites were compared at a 5% significance level. Many of the compared plant species at different sites showed high significant differences $p < 0.0001$, while the smallest significant difference of $p = 0.0452$ was noted for *C. dactylon* at site 1 vs. *C. dactylon* at site 3 (Table 4.1).

Table 4. 1: Comparison of the concentrations of Lead in plant species growing on soil at different sites

Tukey's multiple comparisons test for Concentrations of Lead at different sites	Summary	P- value
<i>C. dactylon</i> :SITE 1 vs. <i>C. dactylon</i> :SITE 3	*	0.0452
<i>C. dactylon</i> :SITE 1 vs. <i>C. dactylon</i> :SITE 4	***	0.0001
<i>C. dactylon</i> :SITE 1 vs. <i>S. acuta</i> :SITE 1	***	0.0003
<i>C. dactylon</i> :SITE 1 vs. <i>S. acuta</i> :SITE 2	*	0.0106
<i>C. dactylon</i> :SITE 1 vs. <i>S. acuta</i> :SITE 3	***	0.0002
<i>C. dactylon</i> :SITE 1 vs. <i>S. acuta</i> :SITE 4	***	0.0001
<i>C. dactylon</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 4	***	0.0001
<i>C. dactylon</i> :SITE 1 vs. <i>P. purpureum</i> :SITE 2	***	0.0001
<i>C. dactylon</i> :SITE 1 vs. <i>P. purpureum</i> :SITE 4	***	0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. dactylon</i> :SITE 4	***	0.0006
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 1	**	0.0012
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 2	*	0.0394
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 3	***	0.0008
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 4	***	0.0005
<i>C. dactylon</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 4	***	0.0005
<i>C. dactylon</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 2	***	0.0006
<i>C. dactylon</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 4	***	0.0007
<i>C. dactylon</i> :SITE 3 vs. <i>C. dactylon</i> :SITE 4	****	<0.0001
<i>C. dactylon</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 2	**	0.0026
<i>C. dactylon</i> :SITE 4 vs. <i>C. benghalensis</i> :SITE 2	****	<0.0001
<i>S. acuta</i> :SITE 1 vs. <i>S. acuta</i> :SITE 2	*	0.0249
<i>S. acuta</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 2	****	<0.0001
<i>S. acuta</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 2	***	0.0005
<i>S. acuta</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 2	****	<0.0001
<i>S. acuta</i> :SITE 4 vs. <i>C. benghalensis</i> :SITE 2	****	<0.0001
<i>C. benghalensis</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 2	****	<0.0001
<i>C. benghalensis</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 4	****	<0.0001
<i>C. benghalensis</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 2	****	<0.0001
<i>C. benghalensis</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 3	*	0.0249
<i>C. benghalensis</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 4	****	<0.0001
<i>C. benghalensis</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 4	****	<0.0001
<i>P. purpureum</i> :SITE 3 vs. <i>P. purpureum</i> :SITE 4	****	<0.0001

Key: *Statistically significant, **Strongly significant, ***Highly significant, ****Extremely significant

4.1.2.2 Cadmium

The study plants were all found to contain Cadmium in their tissues. *C. benghalensis* from site 2 recorded the highest Cadmium concentration at 2.16 mg/kg. *S.acuta* from site 2 also showed elevated Cd levels (1.95 mg/kg), indicating Cd contamination at site 2. *C. dactylon* showed its

highest Cadmium absorption (1.18 mg/kg) at site 2 as well, while it was found low at site 4 (0.26 mg/kg). Notably, *P. purpureum* demonstrated its greatest Cd uptake at site 3 (1.84 mg/kg), differing from the other species that peaked at site 2. For all species, the lowest Cadmium concentrations were recorded at the control site, where levels ranged from 0.26 mg/kg in *C. dactylon* to 0.68 mg/kg in *C. benghalensis* (Figure 4.3).

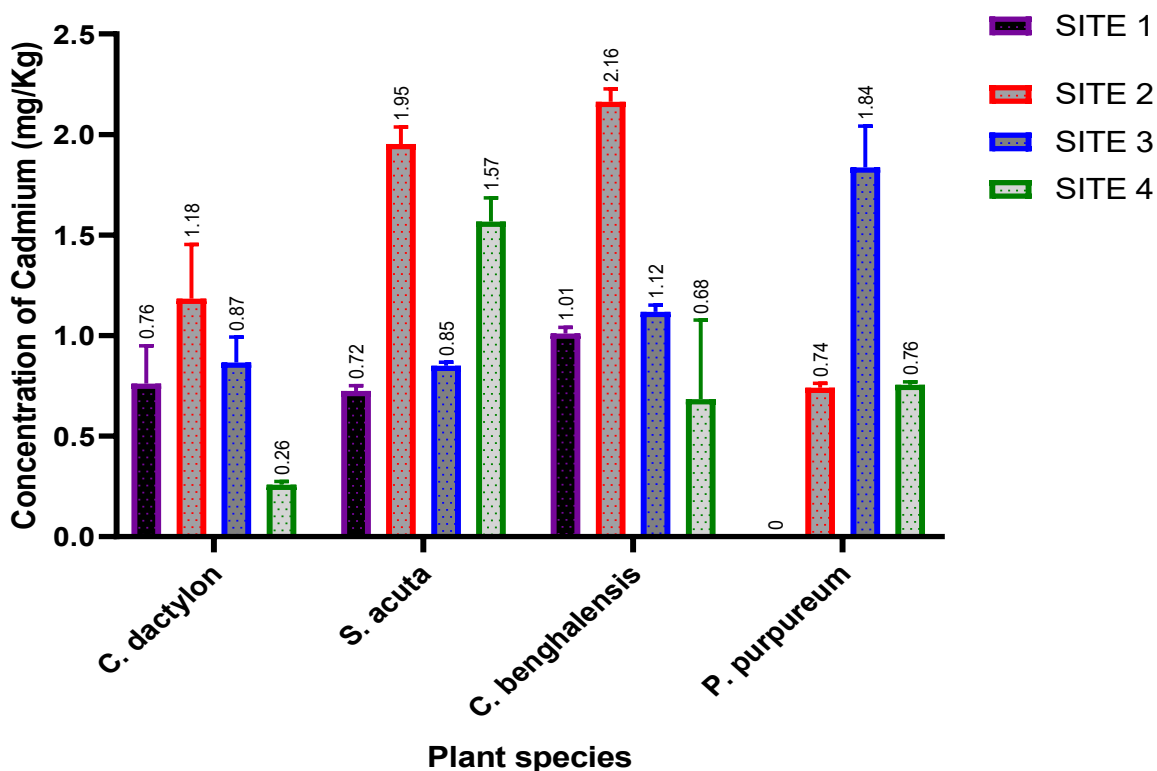


Figure 4. 3: Mean concentrations (mg/kg) of Cadmium in plant species growing on soil at different sites.

The mean concentrations of the Cadmium absorbed by the different plants at the different sites were compared at a 5% significance level. The largest significant difference $p < 0.0001$ was noted for *C. dactylon* at site 4 vs. *S. acuta* at site 3 and *C. dactylon* at site 4 vs. *P. purpureum* at site 4 (Table 4.2).

Table 4. 2: Comparison of the concentrations of Cadmium in plant species growing on soil at different sites

Tukey's multiple comparisons test for Concentrations of Cadmium at different sites	Summary	P -Value
<i>C. dactylon</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 2	*	0.0398
<i>C. dactylon</i> :SITE 3 vs. <i>S. acuta</i> :SITE 2	*	0.0157
<i>C. dactylon</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 2	**	0.0093
<i>C. dactylon</i> :SITE 4 vs. <i>S. acuta</i> :SITE 1	***	0.0006
<i>C. dactylon</i> :SITE 4 vs. <i>S. acuta</i> :SITE 2	**	0.0020
<i>C. dactylon</i> :SITE 4 vs. <i>S. acuta</i> :SITE 3	****	<0.0001
<i>C. dactylon</i> :SITE 4 vs. <i>S. acuta</i> :SITE 4	*	0.0213
<i>C. dactylon</i> :SITE 4 vs. <i>C. benghalensis</i> :SITE 1	***	0.0001
<i>C. dactylon</i> :SITE 4 vs. <i>C. benghalensis</i> :SITE 2	***	0.0007
<i>C. dactylon</i> :SITE 4 vs. <i>C. benghalensis</i> :SITE 3	***	0.0002
<i>C. dactylon</i> :SITE 4 vs. <i>P. purpureum</i> :SITE 2	***	0.0001
<i>C. dactylon</i> :SITE 4 vs. <i>P. purpureum</i> :SITE 3	*	0.0466
<i>C. dactylon</i> :SITE 4 vs. <i>P. purpureum</i> :SITE 4	****	<0.0001
<i>S. acuta</i> :SITE 1 vs. <i>S. acuta</i> :SITE 2	**	0.0046
<i>S. acuta</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 2	***	0.0004
<i>S. acuta</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 3	**	0.0035
<i>S. acuta</i> :SITE 2 vs. <i>S. acuta</i> :SITE 3	**	0.0087
<i>S. acuta</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 1	**	0.0098
<i>S. acuta</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 3	*	0.0135
<i>S. acuta</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 2	**	0.0034
<i>S. acuta</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 4	**	0.0074
<i>S. acuta</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 2	**	0.0013
<i>C. benghalensis</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 2	***	0.0009
<i>C. benghalensis</i> :SITE 1 vs. <i>P. purpureum</i> :SITE 2	*	0.0125
<i>C. benghalensis</i> :SITE 1 vs. <i>P. purpureum</i> :SITE 4	*	0.0209
<i>C. benghalensis</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 3	**	0.0011
<i>C. benghalensis</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 2	**	0.0013
<i>C. benghalensis</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 4	**	0.0013
<i>C. benghalensis</i> :SITE 3 vs. <i>P. purpureum</i> :SITE 2	**	0.0046
<i>C. benghalensis</i> :SITE 3 vs. <i>P. purpureum</i> :SITE 4	**	0.0098

Key: *Statistically significant, **Strongly significant, ***Highly significant, ****Extremely significant

4.1.2.3 Copper

Results from the four studied plants showed accumulated Copper at each site. *C. dactylon* demonstrated the highest Copper accumulation (40.48 mg/kg) at site 3 while at the control site (site 4), it absorbed significantly less Cu (5.18 mg/kg), *C. benghalensis* also showed considerable Cu accumulation, especially at site 2, where it recorded 29.74 mg/kg. Its Cu uptake dropped sharply to

0.54 mg/kg at site 4. *P. purpureum* displayed its highest Cu uptake at site 2 as well (10.41 mg/kg), with a notable decline at the control site (0.48 mg/kg). On the other hand, *S. acuta* showed relatively low Cu uptake across all sites, with the highest concentration being only 2.20 mg/kg at site 2 and the lowest (0.62 mg/kg) at site 1 (Figure 4.4).

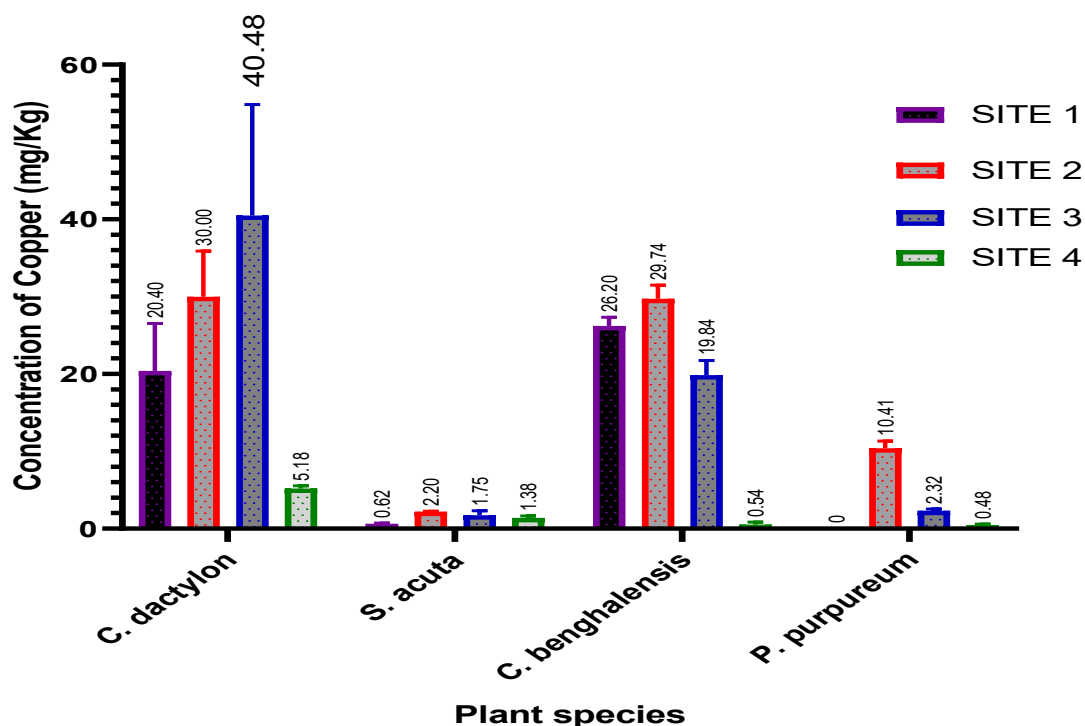


Figure 4. 4: Mean concentrations (mg/kg) of Copper in plant species growing on soil at different sites

The mean concentrations of the Copper absorbed by the different plants at the different sites were compared at a 5% significance level. The largest significant difference was between *S. acuta* at site 3 vs. *C. benghalensis* at site 1; $p = 0.0003$ and *S. acuta* at site 1 vs. *S. acuta* at site 2; $p = 0.0005$ (Table 4.3).

Table 4. 3: Comparison of the concentrations of Copper in plant species growing on soil at different sites

Tukey's multiple comparisons test for Concentrations of Copper at different sites	Summary	P-value
<i>C. dactylon</i> :SITE 4 vs. <i>S. acuta</i> :SITE1	**	0.0094
<i>C. dactylon</i> :SITE 4 vs. <i>S. acuta</i> :SITE 2	*	0.0393
<i>C. dactylon</i> :SITE 4 vs. <i>C. benghalensis</i> :SITE1	**	0.0016
<i>C. dactylon</i> :SITE 4 vs. <i>C. benghalensis</i> :SITE 2	**	0.0066
<i>C. dactylon</i> :SITE 4 vs. <i>C. benghalensis</i> :SITE 3	*	0.0426
<i>C. dactylon</i> :SITE 4 vs. <i>P. purpureum</i> :SITE 3	*	0.0254
<i>C. dactylon</i> :SITE 4 vs. <i>P. purpureum</i> :SITE 4	*	0.0254
<i>S. acuta</i> :SITE1 vs. <i>S. acuta</i> :SITE 2	***	0.0005
<i>S. acuta</i> :SITE1 vs. <i>C. benghalensis</i> :SITE1	**	0.0024
<i>S. acuta</i> :SITE1 vs. <i>C. benghalensis</i> :SITE 2	**	0.0048
<i>S. acuta</i> :SITE1 vs. <i>C. benghalensis</i> :SITE 3	*	0.0220
<i>S. acuta</i> :SITE1 vs. <i>P. purpureum</i> :SITE 2	*	0.0188
<i>S. acuta</i> :SITE1 vs. <i>P. purpureum</i> :SITE 3	*	0.0296
<i>S. acuta</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE1	**	0.0023
<i>S. acuta</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 2	**	0.0055
<i>S. acuta</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 3	*	0.0283
<i>S. acuta</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 2	*	0.0372
<i>S. acuta</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 4	**	0.0021
<i>S. acuta</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE1	***	0.0003
<i>S. acuta</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 2	**	0.0029
<i>S. acuta</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 3	**	0.0097
<i>S. acuta</i> :SITE 3 vs. <i>P. purpureum</i> :SITE 2	*	0.0109
<i>S. acuta</i> :SITE 4 vs. <i>C. benghalensis</i> :SITE1	**	0.0012
<i>S. acuta</i> :SITE 4 vs. <i>C. benghalensis</i> :SITE 2	**	0.0046
<i>S. acuta</i> :SITE 4 vs. <i>C. benghalensis</i> :SITE 3	*	0.0228
<i>S. acuta</i> :SITE 4 vs. <i>C. benghalensis</i> :SITE 4	**	0.0021
<i>S. acuta</i> :SITE 4 vs. <i>P. purpureum</i> :SITE 2	*	0.0174
<i>C. benghalensis</i> :SITE1 vs. <i>C. benghalensis</i> :SITE 4	**	0.0010
<i>C. benghalensis</i> :SITE1 vs. <i>P. purpureum</i> :SITE 2	**	0.0013
<i>C. benghalensis</i> :SITE1 vs. <i>P. purpureum</i> :SITE 3	**	0.0017
<i>C. benghalensis</i> :SITE1 vs. <i>P. purpureum</i> :SITE 4	**	0.0018
<i>C. benghalensis</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 4	**	0.0039
<i>C. benghalensis</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 3	**	0.0055
<i>C. benghalensis</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 4	**	0.0047
<i>C. benghalensis</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 4	*	0.0195
<i>C. benghalensis</i> :SITE 3 vs. <i>P. purpureum</i> :SITE 3	*	0.0391
<i>C. benghalensis</i> :SITE 3 vs. <i>P. purpureum</i> :SITE 4	*	0.0214
<i>C. benghalensis</i> :SITE 4 vs. <i>P. purpureum</i> :SITE 2	*	0.0119
<i>P. purpureum</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 3	*	0.0279
<i>P. purpureum</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 4	*	0.0174
<i>P. purpureum</i> :SITE 3 vs. <i>P. purpureum</i> :SITE 4	*	0.0179

Key: *Statistically significant, **Strongly significant, ***Highly significant

4.1.2.4 Arsenic

C. dactylon and *P. purpureum* were found to contain detectable levels of Arsenic, while *S. acuta* and *C. benghalensis* showed no Arsenic accumulation across any of the four sites. *C. dactylon* showed the highest Arsenic uptake (0.47 mg/kg) recorded at site 2. In contrast, its Arsenic levels were minimal and identical (0.04 mg/kg) at sites 1, 3, and the control site. *P. purpureum* exhibited a more moderate uptake, with concentrations of 0.13 mg/kg at site 2 and 0.09 mg/kg at site (Figure 4.5).

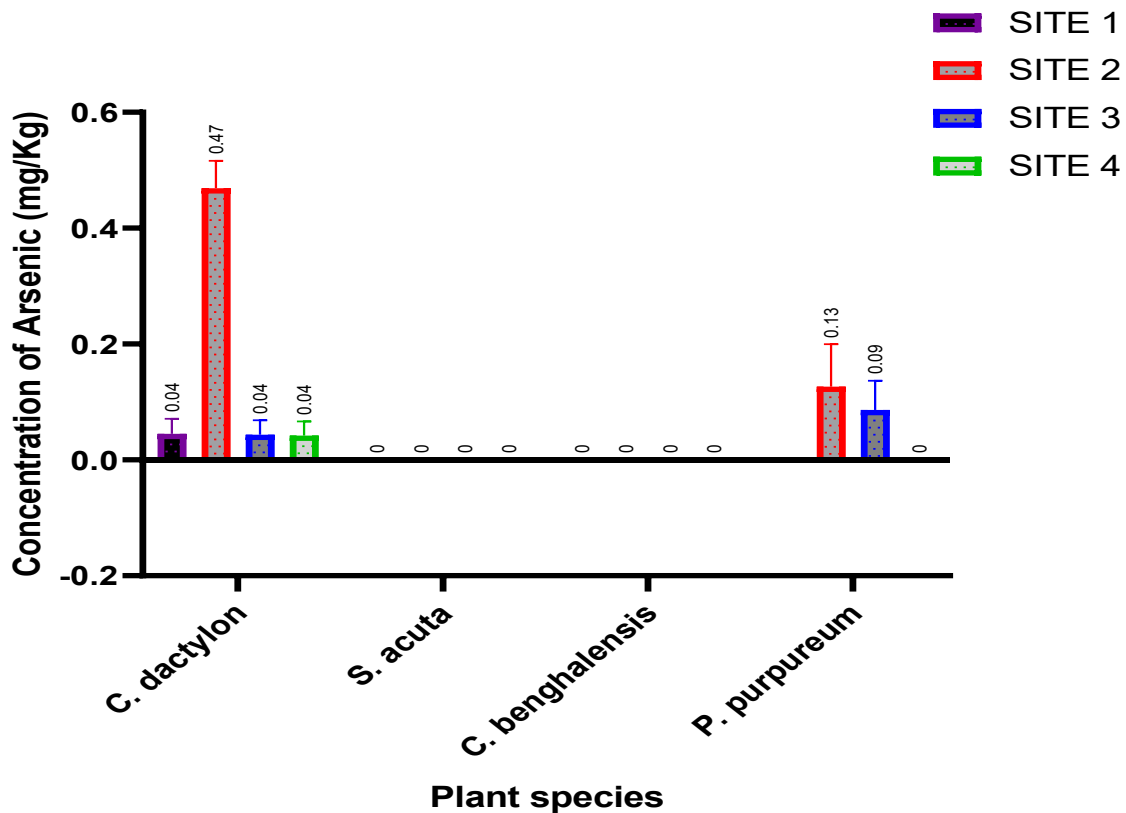


Figure 4. 5: Mean concentrations (mg/kg) of Arsenic in plants growing on soil at different sites

The mean concentrations of the Arsenic absorbed by the different plants at the different sites were compared at a 5% significance level. The results from Tukey's multiple comparisons test for arsenic concentrations reveal highly significant differences ($p < 0.0001$) across various sites and plant species. Notably, *Cynodon dactylon* at site 2 exhibited extremely significant differences when compared to all other sites and species, including *C. dactylon* (sites 1, 3, and 4), *S.acuta* (all sites), *C. benghalensis* (all sites), and *P. purpureum* (sites 2, 3, and 4) (Table 4.4).

Table 4. 4: Comparison of the concentrations of Arsenic in plant species growing on soil at different sites

Tukey's multiple comparisons test for Concentrations of Arsenic at different sites	Summary	P -Value
<i>C. dactylon</i> :SITE 1 vs. <i>C. dactylon</i> :SITE 2	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. dactylon</i> :SITE 3	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. dactylon</i> :SITE 4	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 1	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 2	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 3	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 4	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 1	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 2	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 3	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 4	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 2	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 3	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 4	****	<0.0001

Key: ****Extremely significant

4.2 Ability of selected plant species to absorb and accumulate Lead, Cadmium, Copper and Arsenic from wastewater sediment

4.2.1 Heavy metal concentration in wastewater sediment at different sites

All the wastewater sediment samples collected from the three different sites contained Lead, Cadmium, Copper and Arsenic. At site 1, Lead was the most abundant heavy metal with a mean concentration of 89.71 mg/kg followed by Copper (26.29 mg/kg), Cadmium (1.14 mg/kg) while

Arsenic was the least abundant (0.08 mg/kg). At site 2, Lead was the most abundant heavy metal with a concentration of 90.49 mg/kg, followed by Copper (47.58 mg/kg), Cadmium (0.96 mg/kg), while Arsenic was the least abundant (0.28 mg/kg). At site 3, Lead was again the most abundant heavy metal with a concentration of 52.33 mg/kg, followed by Copper (27.42 mg/kg), Cadmium (1.24 mg/kg), while Arsenic was the least abundant (0.26 mg/kg) (Figure 4.6).

All wastewater sediment samples from the three sites contained Lead, Cadmium, Copper, and Arsenic, with Lead consistently being the most abundant heavy metal at all locations. The highest Lead concentration was observed at site 2, followed closely by site 1, indicating Lead contamination. Copper was the second most prevalent metal, while Cadmium levels remained moderate across all sites. Arsenic was consistently the least abundant metal. Overall, the results point to substantial heavy metal contamination, particularly by Lead and Copper, in the wastewater sediments.

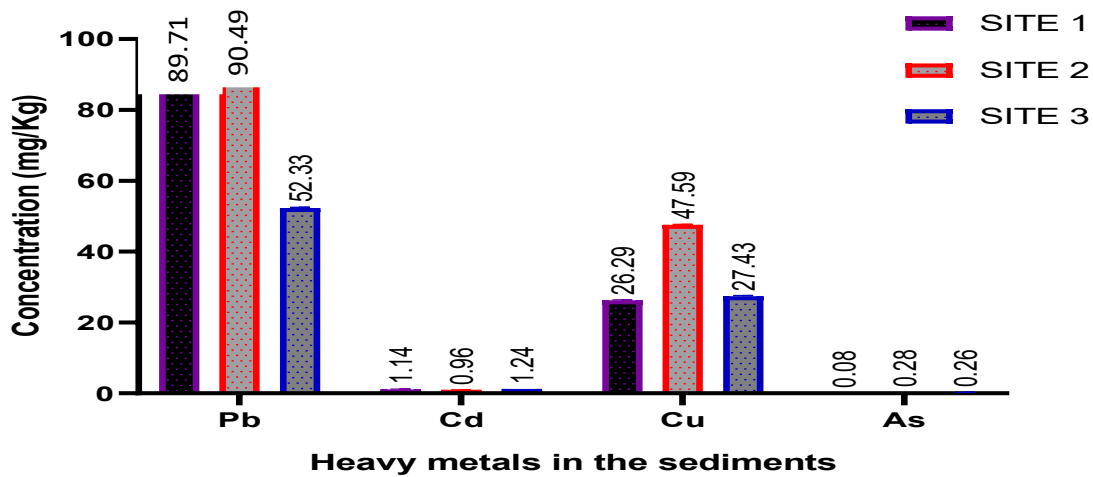


Figure 4. 6: Mean concentrations (mg/kg) of heavy metals in wastewater sediments at different sites

4.2.2 Heavy metal concentration in plant species growing in wastewater sediments

4.2.2.1 Lead

All four studied plant species accumulated Lead in their tissues, confirming the presence of the metal in the wastewater sediments and its bioavailability to vegetation. *C. benghalensis* showed the highest uptake of Lead, with a significant concentration of 32.44 mg/kg at site 2. The same species recorded the lowest uptake at site 1 (13.41 mg/kg). *C. dactylon* also demonstrated substantial Lead accumulation, particularly at site 1 (27.63 mg/kg). Its lowest uptake, but still a notable amount, was at site 3 (9.71 mg/kg). *S. acuta* displayed more moderate Lead absorption compared to the other species. It had its highest Pb concentration at site 2 (7.17 mg/kg), but its uptake dropped at site 3 (0.76 mg/kg). *P. purpureum*, on the other hand, showed a distinct pattern. It accumulated the highest amount of Lead at site 3 (13.44 mg/kg), but had the lowest uptake at site 2 (0.45 mg/kg) (Figure 4.7).

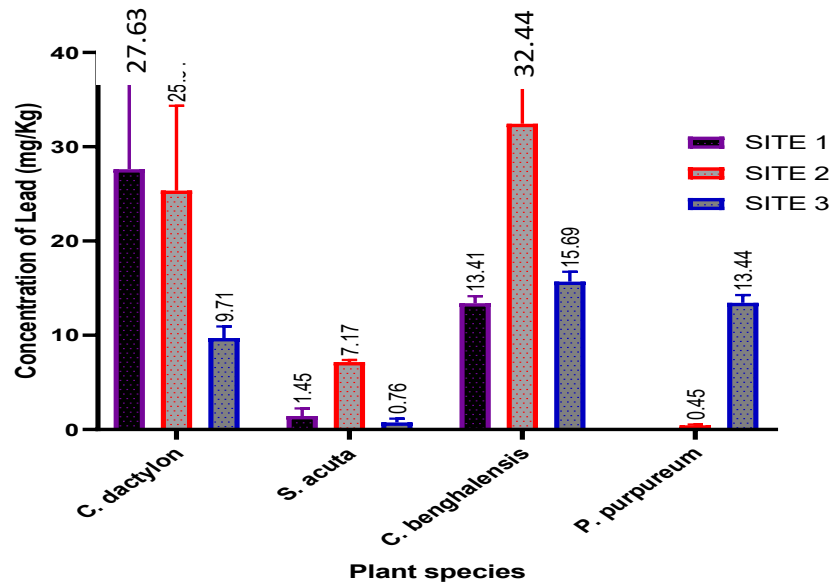


Figure 4. 7: Mean concentrations (mg/kg) of Lead in plants growing on wastewater sediments at different sampling sites

The mean concentrations of the Lead absorbed by the different plants at the different sites were compared at a 5% significance level. The largest significant difference noted was $p < 0.0001$ between a few compared plants at different sites (Table 4.5).

Table 4. 5: Comparison of the concentrations of Lead in plant species growing on wastewater sediments at different sites

Tukey's multiple comparisons test for Concentrations of Lead at different sites	Summary	P- value
<i>C. dactylon</i> :SITE 1 vs. <i>C. dactylon</i> :SITE 3	*	0.0452
<i>C. dactylon</i> :SITE 1 vs. <i>S. acuta</i> :SITE 1	***	0.0003
<i>C. dactylon</i> :SITE 1 vs. <i>S. acuta</i> :SITE 2	*	0.0106
<i>C. dactylon</i> :SITE 1 vs. <i>S. acuta</i> :SITE 3	***	0.0002
<i>C. dactylon</i> :SITE 1 vs. <i>P. purpureum</i> :SITE 2	***	0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 1	**	0.0012
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 2	*	0.0394
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 3	***	0.0008
<i>C. dactylon</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 2	***	0.0006
<i>C. dactylon</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 2	**	0.0026
<i>S. acuta</i> :SITE 1 vs. <i>S. acuta</i> :SITE 2	*	0.0249
<i>S. acuta</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 2	****	<0.0001
<i>S. acuta</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 2	***	0.0005
<i>S. acuta</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 2	****	<0.0001
<i>C. benghalensis</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 2	****	<0.0001
<i>C. benghalensis</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 2	****	<0.0001
<i>C. benghalensis</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 3	*	0.0249

Key: *Statistically significant, **Strongly significant, ***Highly significant, ****Extremely significant

4.2.2.2 Cadmium

All examined species contained detectable levels of Cadmium in their tissues *C. benghalensis* showed the highest Cadmium uptake, particularly at site 2 (2.01 mg/kg). In contrast, the same species absorbed the lowest concentration (0.86 mg/kg) at site 1. At site 2, *S. acuta* absorbed 1.80 mg/kg while *C. dactylon* showed a clear pattern of Cadmium accumulation, with the highest concentration (1.03 mg/kg) from site 2 and the lowest (0.61 mg/kg) from site 1. *P. purpureum*

showed a distinct uptake pattern, with the highest Cadmium concentration recorded at site 3 (1.69 mg/kg) and the lowest at site 2 (0.59 mg/kg) (Figure 4.8).

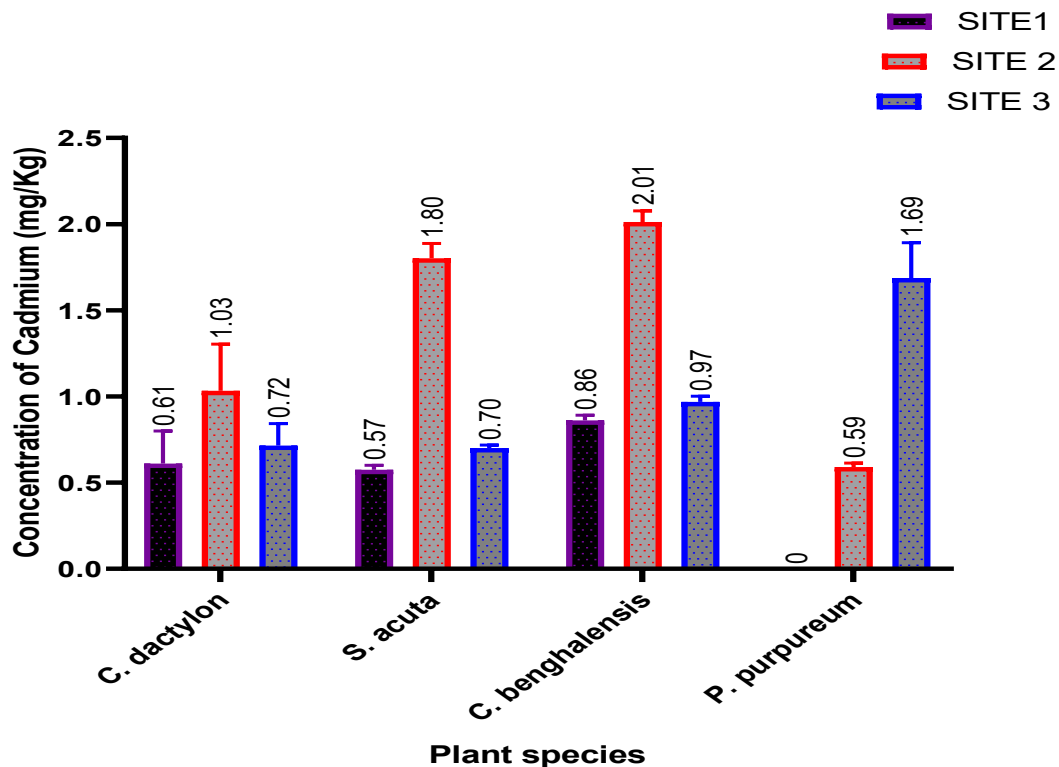


Figure 4. 8: Mean concentrations (mg/kg) of Cadmium in plants growing on wastewater sediments at different sampling sites

The mean concentrations of the Cadmium absorbed by the different plants at the different sites were compared at a 5% significance level. The largest significant difference, $p=0.0004$, was noted for *S. acuta* at site 1 vs. *C. benghalensis* at site 2 (Table 4.6).

Table 4. 6: Comparison of the concentrations of Cadmium in plant species growing on wastewater sediments at different sites

Tukey's multiple comparisons test for Concentrations of Cadmium at different sites	Summary	P- Value
<i>C. dactylon</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 2	*	0.0398
<i>C. dactylon</i> :SITE 3 vs. <i>S. acuta</i> :SITE 2	*	0.0157
<i>C. dactylon</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 2	**	0.0093
<i>S. acuta</i> :SITE 1 vs. <i>S. acuta</i> :SITE 2	**	0.0046
<i>S. acuta</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 2	***	0.0004
<i>S. acuta</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 3	**	0.0035
<i>S. acuta</i> :SITE 2 vs. <i>S. acuta</i> :SITE 3	**	0.0087
<i>S. acuta</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 1	**	0.0098
<i>S. acuta</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 3	*	0.0135
<i>S. acuta</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 2	**	0.0034
<i>S. acuta</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 2	**	0.0013
<i>C. benghalensis</i> :SITE 1 vs. <i>C. benghalensis</i> :SITE 2	***	0.0009
<i>C. benghalensis</i> :SITE 1 vs. <i>P. purpureum</i> :SITE 2	*	0.0125
<i>C. benghalensis</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 3	**	0.0011
<i>C. benghalensis</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 2	**	0.0013
<i>C. benghalensis</i> :SITE 3 vs. <i>P. purpureum</i> :SITE 2	**	0.0046

Key: *Statistically significant, **Strongly significant, ***Highly significant

4.2.2.3 Copper

The studied species contained Copper at all sediment sites. *C. dactylon* showed the highest Copper accumulation (39.68 mg/kg) at site 3. In contrast, *C. dactylon* from site 1 had the lowest Cu concentration (19.60 mg/kg), although it was still relatively high. *C. benghalensis* also showed a substantial ability to accumulate Copper. The highest concentration (28.94 mg/kg) was recorded at site 2, while the lowest (19.04 mg/kg) was found at site 3. *P. purpureum* displayed more variable Copper uptake. It showed its highest Cu concentration (9.61 mg/kg) at site 2 but showed a sharp decline (1.52 mg/kg) at site 3. *S. acuta*, on the other hand, demonstrated relatively low Copper accumulation across all sites. The highest value (1.40 mg/kg) was at site 2, while the lowest (0.62 mg/kg) was at site 1 (Figure 4.9).

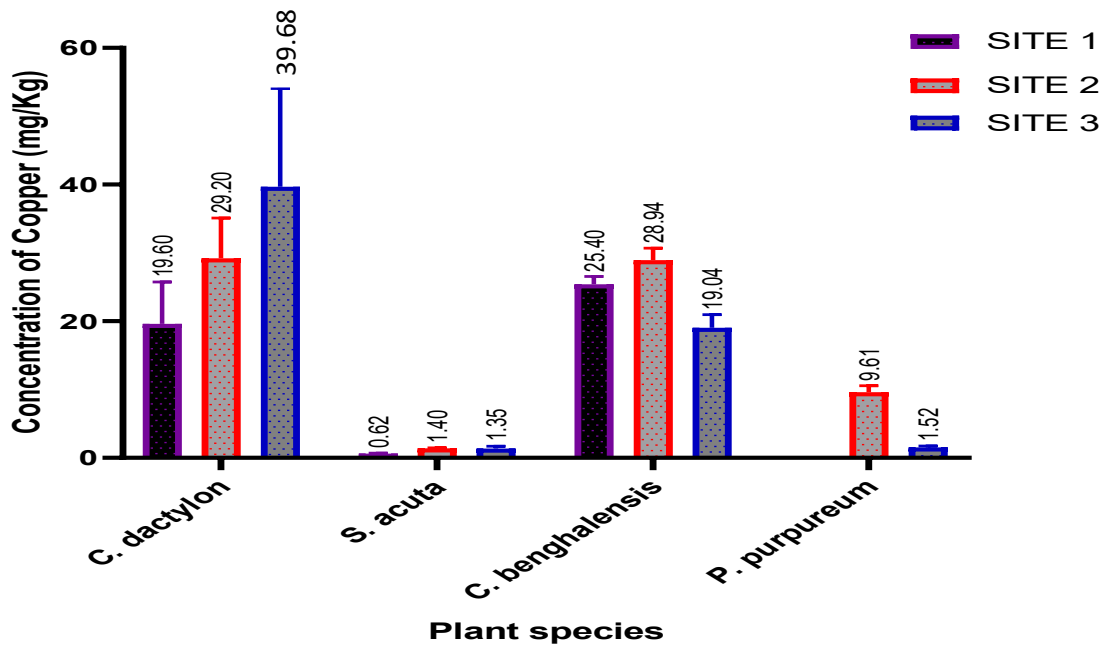


Figure 4. 9: Mean concentrations (mg/kg) of Copper in plants growing on wastewater sediments at different sampling sites.

The mean concentrations of the Copper absorbed by the different plants at the different sites were compared at a 5% significance level. The results showed the highest significant difference ($p = 0.0003$) between *S. acuta* at site 3 vs. *C. benghalensis* at site 1 (Table 4.7).

Table 4. 7: Comparison of the concentrations of Copper in plant species growing on wastewater sediments at different sites

Tukey's multiple comparisons test for Concentrations of Copper at different sites		
	Summary	P-value
<i>S. acuta</i> :SITE1 vs. <i>S. acuta</i> :SITE 2	***	0.0005
<i>S. acuta</i> :SITE1 vs. <i>C. benghalensis</i> :SITE1	**	0.0024
<i>S. acuta</i> :SITE1 vs. <i>C. benghalensis</i> :SITE 2	**	0.0048
<i>S. acuta</i> :SITE1 vs. <i>C. benghalensis</i> :SITE 3	*	0.0220
<i>S. acuta</i> :SITE1 vs. <i>P. purpureum</i> :SITE 2	*	0.0188
<i>S. acuta</i> :SITE1 vs. <i>P. purpureum</i> :SITE 3	*	0.0296
<i>S. acuta</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE1	**	0.0023
<i>S. acuta</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 2	**	0.0055
<i>S. acuta</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 3	*	0.0283
<i>S. acuta</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 2	*	0.0372
<i>S. acuta</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE1	***	0.0003
<i>S. acuta</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 2	**	0.0029
<i>S. acuta</i> :SITE 3 vs. <i>C. benghalensis</i> :SITE 3	**	0.0097
<i>S. acuta</i> :SITE 3 vs. <i>P. purpureum</i> :SITE 2	*	0.0109
<i>C. benghalensis</i> :SITE1 vs. <i>P. purpureum</i> :SITE 2	**	0.0013
<i>C. benghalensis</i> :SITE1 vs. <i>P. purpureum</i> :SITE 3	**	0.0017
<i>C. benghalensis</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 3	**	0.0055
<i>C. benghalensis</i> :SITE 3 vs. <i>P. purpureum</i> :SITE 3	*	0.0391
<i>C. benghalensis</i> :SITE 4 vs. <i>P. purpureum</i> :SITE 2	*	0.0119
<i>P. purpureum</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 3	*	0.0279

Key: *Statistically significant, **Strongly significant, ***Highly significant

4.2.2.4 Arsenic

Among the four studied species, only *C. dactylon* and *P. purpureum* demonstrated Arsenic uptake, while *S. acuta* and *C. benghalensis* showed no detectable levels of Arsenic in their tissues across all sites. *C. dactylon* recorded the highest Arsenic accumulation at site 2 (0.33 mg/kg) while at sites 1, 3, and 4, the plant showed minimal absorption (0.03 mg/kg). *P. purpureum* also showed low but measurable Arsenic concentrations, detected at site 2 (0.09 mg/kg) and at site 3 (0.06 mg/kg). In summary, arsenic was present in only two of the four species, and at relatively low concentrations (Figure 4.10).

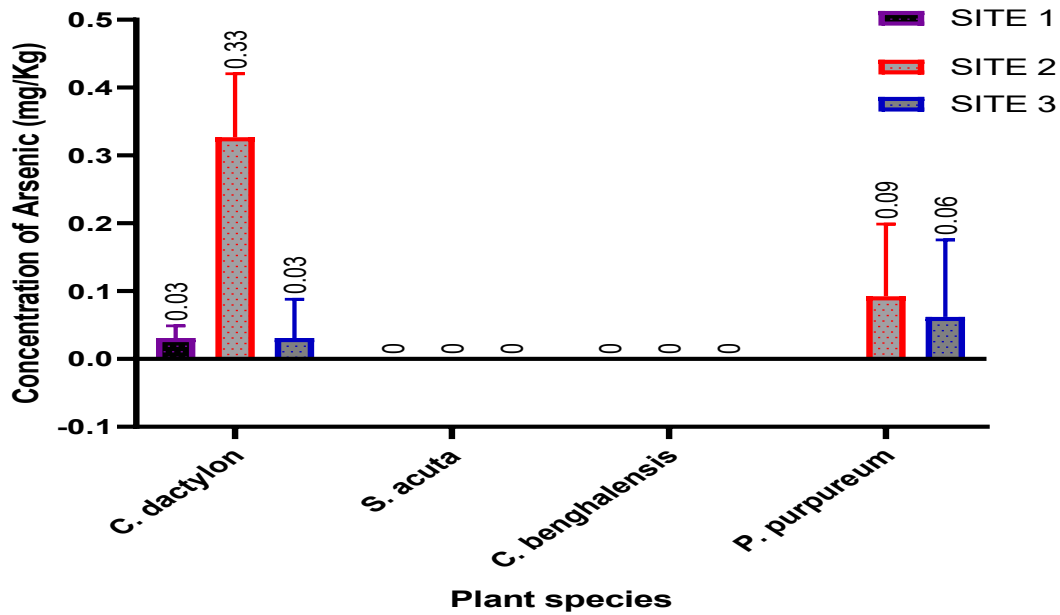


Figure 4. 10: Mean concentrations (mg/kg) of Arsenic in plants growing on wastewater sediments at different sampling sites.

The mean concentrations of the Arsenic absorbed by the different plants at the different sites were compared at a 5% significance level. The Tukey's multiple comparisons test indicated highly significant differences ($p < 0.0001$) in Arsenic concentrations across various sites and plant species. *Cynodon dactylon* at site 2 exhibited significantly different Arsenic levels compared to all other species at different sites (Table 4.8).

Table 4. 8: Comparison of the concentrations of Arsenic in plant species growing on wastewater sediments at different sites

Tukey's multiple comparisons test for Concentrations of Arsenic at different sites	Summary	P -Value
<i>C. dactylon</i> :SITE 1 vs. <i>C. dactylon</i> :SITE 2	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. dactylon</i> :SITE 3	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. dactylon</i> :SITE 4	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 1	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 2	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 3	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>S. acuta</i> :SITE 4	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 1	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 2	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 3	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>C. benghalensis</i> :SITE 4	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 2	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 3	****	<0.0001
<i>C. dactylon</i> :SITE 2 vs. <i>P. purpureum</i> :SITE 4	****	<0.0001

Key: ****Extremely significant

4.3 Mechanism of phytoremediation by which plant species uptake Lead, Cadmium, Copper, and Arsenic from soil and wastewater sediments at different sites

Determination of the mechanism of phytoremediation by which *C. benghalensis*, *P. purpureum*, *S. acuta* and *C. dactylon* take up Lead, Cadmium, Copper and Arsenic from soil and wastewater sediments was done by calculating Bio-concentration factor (BCF), Translocation Factor (TF), Biological Absorption Coefficient (BAC) and the results are shown in tables.

4.3.1 Accumulation of heavy metals in the plant parts (plants growing on soil)

At site 1, Lead was the most abundant heavy metal in soil with a concentration of 70.18 mg/kg, followed by Copper (52.09 mg/kg), Cadmium (1.15 mg/kg), while Arsenic was the least abundant (1.02 mg/kg). *C. dactylon* roots accumulated the highest amounts of Lead (44.71 mg/kg), Cadmium (1.09 mg/kg), and Copper (31.04 mg/kg) while *C. dactylon* shoot accumulated the highest amounts of Arsenic (0.16 mg/kg). At site 2, Lead was the most abundant heavy metal with a concentration of 83.48 mg/kg followed by Copper (34.67 mg/kg mg/kg), Cadmium (1.26 mg/kg) while Arsenic was

the least abundant (0.65 mg/kg). *C. dactylon* roots accumulated the highest amounts of Lead (41.73 mg/kg), Copper (40.21 mg/kg), and Arsenic (0.40 mg/kg) while *C. benghalensis* roots accumulated the highest amounts of Cadmium (2.27 mg/kg). At site 3, Lead was the most abundant heavy metal with a concentration of 25.36 mg/kg, followed by Copper (24.31 mg/kg), Cadmium (1.49 mg/kg), while Arsenic was the least abundant (1.24 mg/kg). *C. benghalensis* roots accumulated the highest amounts of Lead (18.31 mg/kg), *P. purpureum* shoots accumulated the highest amount of Cadmium (2.19 mg/kg), *C. dactylon* roots accumulated the highest amount of Copper (65.35 mg/kg), while *P. purpureum* roots accumulated the highest amounts of Arsenic (0.0 mg/kg). At site 4, Copper was the most abundant heavy metal with a concentration of 5.64 mg/kg, followed by Lead (4.66 mg/kg), Cadmium (0.65 mg/kg), while soil samples from site 4 did not contain Arsenic. *C. benghalensis* roots accumulated the highest amounts of Lead (1.96 mg/kg), *S. acuta* shoot accumulated the highest amount of Cadmium (1.77 mg/kg), *C. dactylon* roots accumulated the highest amount of Copper (5.82 mg/kg), while *C. dactylon* shoot accumulated the largest sum of Arsenic (0.06 mg/kg) (Table 4.9).

Table 4. 9: Mean concentrations (mg/kg) of heavy metals in the parts of the plants growing on soil

Site	Plant species	Plant parts	Heavy metal concentration (Mean ± S.E)				
			Pb	Cd	Cu	As	
SITE 1	<i>C. dactylon</i>	Shoot	12.15±0.00	0.43±0.00	9.76±0.02	0.16±0.00	
		Roots	44.71±0.14	1.09±0.03	31.04±0.06	0.00±0.00	
	<i>S. acuta</i>	Shoot	0.86±0.00	0.77±0.02	0.77±0.02	0.00±0.00	
		Roots	3.63±0.03	0.68±0.00	0.47±0.03	0.00±0.00	
	<i>C. benghalensis</i>	Shoot	12.94±0.02	0.96±0.03	24.24±0.05	0.00±0.00	
		Roots	15.49±0.13	1.06±0.00	28.17±0.13	0.00±0.00	
		Soil	70.18±0.07	1.15±0.03	52.09±0.01	1.02±0.04	
	SITE 2	<i>C. dactylon</i>	Shoot	10.55±0.14	0.72±0.03	19.79±0.03	0.25±0.00
			Roots	41.73±0.11	1.65±0.03	40.21±0.05	0.40±0.03
<i>S. acuta</i>		Shoot	7.60±0.00	1.82±0.07	2.28±0.09	0.00±0.00	
		Roots	8.33±0.03	2.09±0.03	2.12±0.00	0.00±0.00	
<i>C. benghalensis</i>		Shoot	25.84±0.00	2.06±0.01	32.76±0.03	0.00±0.00	
		Roots	40.65±0.35	2.27±0.06	26.72±0.23	0.00±0.00	
<i>P. purpureum</i>		Shoot	1.12±0.00	0.71±0.03	8.80±0.05	0.00±0.00	
		Roots	1.38±0.02	0.77±0.02	12.02±0.04	0.18±0.00	
Soil			83.48±0.16	1.26±0.02	34.67±0.04	0.65±0.01	
SITE 3		<i>C. dactylon</i>	Shoot	8.39±0.19	0.65±0.02	10.08±0.33	0.00±0.00
			Roots	12.62±0.03	1.09±0.02	65.35±0.03	0.06±0.00
		<i>S. acuta</i>	Shoot	2.25±0.00	0.87±0.02	2.73±0.06	0.00±0.00
	Roots		0.86±0.05	0.83±0.02	0.77±0.02	0.00±0.00	
	<i>C. benghalensis</i>	Shoot	14.67±0.09	1.06±0.00	23.15±0.02	0.00±0.00	
		Roots	18.31±0.018	1.18±0.00	16.54±0.09	0.00±0.00	
	<i>P. purpureum</i>	Shoot	12.82±0.15	2.19±0.02	1.94±0.03	0.00±0.00	
		Roots	15.65±0.11	1.48±0.06	2.69±0.03	0.12±0.00	
	Soil		25.36±0,29	1.49±0.02	24.31±0.16	1.24±0.02	
	SITE 4	<i>C. dactylon</i>	Shoot	1.11±0.02	0.24±0.00	4.54±0.04	0.06±0.00
			Roots	1.23±0.05	0.28±0.03	5.82±0.03	0.00±0.00
		<i>S. acuta</i>	Shoot	0.93±0.00	1.77±0.03	1.86±0.06	0.00±0.00
Roots			0.78±0.03	1.37±0.00	0.90±0.03	0.00±0.00	
<i>C. benghalensis</i>		Shoot	0.00±0.00	0.00±0.00	1.07±0.02	0.00±0.00	
		Roots	1.96±0.03	1.37±0.00	0.00±0.00	0.00±0.00	
<i>P. purpureum</i>		Shoot	1.18±0.00	0.74±0.00	0.68±0.00	0.00±0.00	
		Roots	1.54±0.06	0.77±0.03	0.28±0.03	0.00±0.00	
Soil			4.66±0.07	0.65±0.00	5.64±0.07	0.00±0.00	

At site 1, the study assessed the bio-concentration factor (BCF), translocation factor (TF), and biological absorption coefficient (BAC) of three plant species—*C. dactylon*, *S. acuta*, and *C. benghalensis* — growing in contaminated soil . *C. dactylon* exhibited the highest BCF values for Lead (0.64), Cadmium (0.95), and Copper (0.60). However, Arsenic was not detected in this species (BCF = 0.00). Its TF values ranged from 0.27 (Pb), 0.40 (Cd) and 0.31 (Cu). The BAC values were highest for Copper (0.19) and Cadmium (0.38). *S. acuta* showed a relatively low BCF for Lead (0.05), Cadmium (0.60), and Copper (0.01), with no accumulation of Arsenic (BCF = 0.00). However, its TF values were notably high for Cadmium (1.12) and Copper (1.65). The BAC for Cadmium (0.67) was the highest among all indices measured for this species. *C. benghalensis* demonstrated moderate to high BCF values, particularly for Cadmium (0.92) and Copper (0.54). It also had the highest TF for Lead (0.84) and Copper (0.86). The BAC values were highest for Copper (0.47) and Cadmium (0.84) (Table 4.10).

Table 4. 10: Mechanism of phytoremediation by which selected plant species take up heavy metals from contaminated soil at site 1

Plant species	Indices	Heavy metals			
		Lead	Cadmium	Copper	Arsenic
<i>Cynodon dactylon</i>	BCF	0.64	0.95	0.60	0.00
	TF	0.27	0.40	0.31	0.00
	BAC	0.17	0.38	0.19	0.15
<i>Sida acuta</i>	BCF	0.05	0.60	0.01	0.00
	TF	0.24	1.12	1.65	0.00
	BAC	0.01	0.67	0.01	0.00
<i>Commelina benghalensis</i>	BCF	0.22	0.92	0.54	0.00
	TF	0.84	0.91	0.86	0.00
	BAC	0.18	0.84	0.47	0.00

BCF: Bio-concentration factor, **TF:** Translocation Factor, **BAC:** Biological Absorption Coefficient

At site 2, *C. dactylon* showed strong potential to retain Cd (BCF = 1.31, BAC = 0.57), Cu (BCF = 1.16, BAC = 0.57), and As (BCF = 0.62, BAC = 0.38) in the roots. *S. acuta* was highly effective in accumulating Cd to aerial parts (BCF = 1.66, BAC = 1.44, TF = 0.87), with moderate Cu

translocation (TF = 1.07). *C. benghalensis* demonstrated the best accumulation efficiency, particularly for Cd (BCF = 1.80, BAC = 1.64, TF = 0.91) and Cu (BCF = 0.77, BAC = 0.94, TF = 1.23) due to its high translocation rates. *P. purpureum* showed moderate Cd uptake (BCF = 0.61, BAC = 0.57) but was less efficient overall (Table 4.11).

Table 4. 11: Mechanism of phytoremediation by which selected plant species take up heavy metals from contaminated soil at site 2

Plant species	Indices	Heavy metals			
		Lead	Cadmium	Copper	Arsenic
<i>Cynodon dactylon</i>	BCF	0.50	1.31	1.16	0.62
	TF	0.25	0.43	0.49	0.61
	BAC	0.13	0.57	0.57	0.38
<i>Sida acuta</i>	BCF	0.10	1.66	0.06	0.00
	TF	0.91	0.87	1.07	0.00
	BAC	0.09	1.44	0.07	0.00
<i>Commelina benghalensis</i>	BCF	0.49	1.80	0.77	0.00
	TF	0.64	0.91	1.23	0.00
	BAC	0.31	1.64	0.94	0.00
<i>Pennisetum purpureum</i>	BCF	0.02	0.61	0.35	0.28
	TF	0.81	0.93	0.73	0.00
	BAC	0.01	0.57	0.25	0.00

BCF: Bio-concentration factor, **TF:** Translocation Factor, **BAC:** Biological Absorption Coefficient

At site 3, *C. dactylon* exhibited the highest BCF for Copper (2.69) but showed low values for other metals. *S. acuta* demonstrated a strong translocation ability, particularly for Lead (TF = 2.62) and Copper (TF = 3.56). *C. benghalensis* recorded relatively high BCF and BAC values for all metals except Arsenic, with a notable Copper BAC of 0.95. *P. purpureum* had the highest BCF for Cadmium (0.99) and a TF of 1.47 for the same metal. Arsenic accumulation was minimal across all species (Table 4.12).

Table 4. 12: Mechanism of phytoremediation by which selected plant species take up heavy metals from contaminated soil at site 3

Plant species	Indices	Heavy metals			
		Lead	Cadmium	Copper	Arsenic
<i>Cynodon dactylon</i>	BCF	0.50	0.73	2.69	0.05
	TF	0.66	0.59	0.15	0.00
	BAC	0.33	0.43	0.41	0.00
<i>Sida acuta</i>	BCF	0.03	0.56	0.03	0.00
	TF	2.62	1.05	3.56	0.00
	BAC	0.09	0.58	0.11	0.00
<i>Commelina benghalensis</i>	BCF	0.72	0.79	0.68	0.00
	TF	0.80	0.90	1.40	0.00
	BAC	0.58	0.71	0.95	0.00
<i>Pennisetum purpureum</i>	BCF	0.62	0.99	0.11	0.10
	TF	0.82	1.47	0.72	0.00
	BAC	0.51	1.47	0.08	0.00

BCF: Bio-concentration factor, **TF:** Translocation Factor, **BAC:** Biological Absorption Coefficient

At site 4, the study evaluated the accumulation and translocation of heavy metals from soil in four plant species (*C. dactylon*, *S. acuta*, *C. benghalensis*, and *P. purpureum*) using three indices: bio-concentration factor (BCF), translocation factor (TF), and biological absorption coefficient (BAC). *S. acuta* showed the highest Cadmium uptake, with a BCF of 2.10 and a BAC of 2.72, along with high translocation (TF = 1.29). *C. dactylon* exhibited the highest Copper accumulation (BCF = 1.03, BAC = 0.80), while *P. purpureum* had the highest Copper translocation (TF = 2.47). *C. benghalensis* demonstrated high Cadmium uptake (BCF = 2.10) but no significant translocation. Arsenic was not detected in any plant (Table 4.13).

Table 4. 13: Mechanism of phytoremediation by which selected plant species take up heavy metals from contaminated soil at site 4

Plant species	Indices	Heavy metals			
		Lead	Cadmium	Copper	Arsenic
<i>Cynodon dactylon</i>	BCF	0.26	0.43	1.03	0.00
	TF	0.90	0.87	0.78	0.00
	BAC	0.24	0.37	0.80	0.00
<i>Sida acuta</i>	BCF	0.17	2.10	0.16	0.00
	TF	1.20	1.29	2.07	0.00
	BAC	0.20	2.72	0.33	0.00
<i>Commelina benghalensis</i>	BCF	0.42	2.10	0.00	0.00
	TF	0.00	0.00	0.00	0.00
	BAC	0.00	0.00	0.19	0.00
<i>Pennisetum purpureum</i>	BCF	0.33	1.18	0.05	0.00
	TF	0.77	0.97	2.47	0.00
	BAC	0.25	1.14	0.12	0.00

BCF: Bio-concentration factor, **TF:** Translocation Factor, **BAC:** Biological Absorption Coefficient

4.3.2 Accumulation of heavy metals in the plant parts at different sites (plants growing in wastewater sediment)

The efficiency of *Commelina benghalensis*, *Pennisetum purpureum*, *Sida acuta* and *Cynodon dactylon* for phytoremediation of Lead, Cadmium, Copper and Arsenic from wastewater sediments in Nakivubo wetland was evaluated. With a concentration of 89.71 mg/kg, Lead was the most prevalent heavy metal at site 1, followed by Copper (26.29 mg/kg), Cadmium (1.14 mg/kg), and Arsenic (0.08 mg/kg), in that order. Lead (43.91 mg/kg), Cadmium (0.94 mg/kg), and Copper (30.24 mg/kg) were most abundantly deposited in *C. dactylon* roots, whereas Arsenic (0.15 mg/kg) was most abundant in *C. dactylon* shoots. With a concentration of 90.49 mg/kg, Lead was the most prevalent heavy metal at site 2, followed by Copper (47.58 mg/kg), Cadmium (0.96 mg/kg), and Arsenic (0.28 mg/kg), in that order. The highest amounts of Lead (40.93 mg/kg), Copper (39.41 mg/kg), and Arsenic (0.40 mg/kg) were accumulated by *C. dactylon* roots, while the highest amounts of Cadmium (2.11 mg/kg) were accumulated by *C. benghalensis* roots. With a concentration of 52.33 mg/kg, Lead was the most prevalent heavy metal at site 3, followed by Copper (27.42 mg/kg),

Cadmium (1.24 mg/kg), and Arsenic (0.26 mg/kg), in that order. The highest amounts of Lead (17.51 mg/kg) were found in *C. benghalensis* roots; the highest amounts of Cadmium (2.04 mg/kg) were found in *P. purpureum* shoots; the highest amounts of Copper (64.55 mg/kg) were found in *C. dactylon* roots; and the highest amounts of Arsenic (0.12 mg/kg) were found in *P. purpureum* roots (Table 4.14).

Table 4. 14: Mean concentrations (mg/kg) of heavy metals in the parts of the plants growing on wastewater sediments at different sites

Site	Plant species	Plant parts	Heavy metal concentrations (Mean ± S.E)				
			Pb	Cd	Cu	As	
SITE 1	<i>C. dactylon</i>	Shoot	11.35±0.00	0.28±0.00	8.96±0.02	0.15±0.00	
		Roots	43.91±0.14	0.94±0.03	30.24±0.06	0.00±0.00	
	<i>Sida acuta</i>	Shoot	0.06±0.00	0.62±0.02	0.77±0.02	0.00±0.00	
		Roots	2.83±0.03	0.53±0.00	1.32±0.03	0.00±0.00	
	<i>C. benghalensis</i>	Shoot	12.14±0.02	0.81±0.03	23.43±0.05	0.00±0.00	
		Roots	37.85±0.13	0.91±0.00	27.37±0.13	0.00±0.00	
		Sediments	89.71±0.00	1.14±0.02	26.29±0.14	0.08±0.00	
	SITE 2	<i>C. dactylon</i>	Shoot	9.75±0.14	0.56±0.03	18.99±0.03	0.25±0.00
			Roots	40.93±0.11	1.50±0.03	39.41±0.05	0.40±0.00
<i>S. acuta</i>		Shoot	6.80±0.00	1.66±0.07	1.48±0.09	0.00±0.00	
		Roots	7.52±0.03	1.94±0.03	1.32±0.00	0.00±0.00	
<i>C. benghalensis</i>		Shoot	25.04±0.00	1.91±0.01	31.96±0.03	0.00±0.00	
		Roots	39.85±0.35	2.11±0.06	25.92±0.22	0.00±0.00	
<i>P. purpureum</i>		Shoot	0.31±0.00	0.56±0.03	8.00±0.05	0.00±0.00	
		Roots	0.58±0.01	0.62±0.02	11.22±0.04	0.18±0.00	
		Sediments	90.49±0.30	0.96±0.04	47.58±0.09	0.28±0.00	
SITE 3	<i>C. dactylon</i>	Shoot	7.59±0.19	0.49±0.02	14.81±0.33	0.00±0.00	
		Roots	11.82±0.03	0.94±0.03	64.55±0.03	0.06±0.00	
	<i>S. acuta</i>	Shoot	1.45±0.00	0.72±0.02	1.93±0.06	0.00±0.00	
		Roots	0.06±0.05	0.68±0.02	0.77±0.02	0.00±0.00	
	<i>C. benghalensis</i>	Shoot	13.87±0.09	0.91±0.00	22.34±0.02	0.00±0.00	
		Roots	17.51±0.18	1.03±0.00	15.74±0.09	0.00±0.00	
	<i>P. purpureum</i>	Shoot	12.02±0.15	2.04±0.02	1.14±0.03	0.00±0.00	
		Roots	14.85±0.11	1.33±0.06	1.89±0.03	0.12±0.00	
		Sediments	52.33±0.19	1.24±0.00	27.42±0.15	0.26±0.02	

The study at site 1 assessed heavy metal accumulation and translocation in *C. dactylon*, *S. acuta*, and *C. benghalensis* (growing on wastewater sediments) using bio-concentration factor (BCF), translocation factor (TF), and biological absorption coefficient (BAC). *C. dactylon* showed the highest Copper uptake (BCF = 1.15, BAC = 0.34), though its translocation was low (TF = 0.30). *C. benghalensis* demonstrated significant Copper accumulation (BCF = 1.04, BAC = 0.89) with moderate translocation (TF = 0.86). *S. acuta* exhibited the highest Cadmium translocation (TF = 1.17) but relatively low accumulation. Arsenic uptake was minimal in all species, except for *C. dactylon*, which had a BAC value of 1.88 (Table 4.15).

Table 4. 15 Mechanism of phytoremediation by which selected plant species take up heavy metals from wastewater sediments at site 1

Plant species	Indices	Pb	Cd	Cu	As
<i>Cynodon dactylon</i>	BCF	0.49	0.82	1.15	0.00
	TF	0.26	0.30	0.30	0.00
	BAC	0.13	0.25	0.34	1.88
<i>Sida acuta</i>	BCF	0.03	0.46	0.05	0.00
	TF	0.02	1.17	0.58	0.00
	BAC	0.00	0.54	0.03	0.00
<i>Commelina benghalensis</i>	BCF	0.42	0.80	1.04	0.00
	TF	0.32	0.89	0.86	0.00
	BAC	0.14	0.71	0.89	0.00

BCF: Bio-concentration factor, **TF:** Translocation Factor, **BAC:** Biological Absorption Coefficient

At site 2, *C. benghalensis* exhibited the highest Cadmium uptake (BCF = 2.20, BAC = 2.20) with strong translocation (TF = 0.91). *S. acuta* also demonstrated high Cadmium accumulation (BCF = 2.02, BAC = 1.73) and moderate translocation (TF = 0.86). *P. purpureum* showed an extremely high Cadmium translocation factor (TF = 31.00) despite its low uptake. *C. dactylon* accumulated significant amounts of Arsenic (BCF = 1.43, BAC = 0.89) with moderate translocation (TF = 0.63) (Table 4.16).

Table 4. 16 Mechanism of phytoremediation by which selected plant species take up heavy metals from wastewater sediments at site 2

Plant species	Indices	Heavy metals			
		Lead	Cadmium	Copper	Arsenic
<i>Cynodon dactylon</i>	BCF	0.45	1.56	0.83	1.43
	TF	0.24	0.37	0.48	0.63
	BAC	0.11	0.58	0.40	0.89
<i>Sida acuta</i>	BCF	0.08	2.02	0.03	0.00
	TF	0.90	0.86	1.12	0.00
	BAC	0.08	1.73	0.03	0.00
<i>Commelina benghalensis</i>	BCF	0.44	2.20	0.54	0.00
	TF	0.63	0.91	1.23	0.00
	BAC	0.44	2.20	0.54	0.00
<i>Pennisetum purpureum</i>	BCF	0.01	0.02	0.24	0.64
	TF	0.53	31.00	0.71	0.00
	BAC	0.00	0.65	0.17	0.00

BCF: Bio-concentration factor, **TF:** Translocation Factor, **BAC:** Biological Absorption Coefficient

At site 3, *C.dactylon* exhibited the highest Copper uptake (BCF = 2.35, BAC = 0.54) but had low translocation (TF = 0.23). *S. acuta* showed an extremely high lead translocation factor (TF = 24.17) despite negligible Lead uptake. *C. benghalensis* demonstrated notable Cadmium accumulation (BCF = 0.83, BAC = 0.73) and moderate translocation (TF = 0.88). *P. purpureum* exhibited the highest Cadmium BAC (1.65) with significant translocation (TF = 1.53). Arsenic uptake was minimal across all species (Table 4.17).

Table 4. 17 Mechanism of phytoremediation by which selected plant species take up heavy metals from wastewater sediments at site 3

Plant species	Indices	Heavy metals			
		Lead	Cadmium	Copper	Arsenic
<i>Cynodon dactylon</i>	BCF	0.23	0.76	2.35	0.23
	TF	0.64	0.52	0.23	0.00
	BAC	0.15	0.40	0.54	0.00
<i>Sida acuta</i>	BCF	0.00	0.55	0.03	0.00
	TF	24.17	1.06	2.51	0.00
	BAC	0.03	0.58	0.07	0.00
<i>Commelina benghalensis</i>	BCF	0.33	0.83	0.57	0.00
	TF	0.79	0.88	1.42	0.00
	BAC	0.27	0.73	0.81	0.00
<i>Pennisetum purpureum</i>	BCF	0.28	1.07	0.07	0.46
	TF	0.81	1.53	0.60	0.00
	BAC	0.23	1.65	0.04	0.00

BCF: Bio-concentration factor, **TF:** Translocation Factor, **BAC:** Biological Absorption Coefficient

CHAPTER FIVE: DISCUSSION OF RESULTS

5.1 Soil contamination

The study results showed that heavy metal concentrations in soil were, on average, higher across all sites. According to WHO (1996), the threshold values for soil contamination by specific metals are Pb (85 mg/kg), Cd (0.8 mg/kg), Cu (36 mg/kg), and As (20 mg/kg). Site-specific variations were observed, with Lead (Pb) consistently being the most abundant metal at sites 1, 2, and 3. This suggests a clear spatial variation in Pb contamination, likely linked to anthropogenic activities near the first three sites. The elevated levels of Pb at these sites may indicate localised pollution sources, such as industrial discharge, vehicular emissions, or improper waste disposal, suggesting a significant human impact. In contrast, the dominance of Cu at the control site implies more natural background conditions or minor agricultural runoff (since Cu is used in fungicides), supporting its role as a reference point for assessing contamination. The bioavailability of all heavy metals at the control site was generally lower than at the other sites, likely due to its distance from the wastewater channel, suggesting reduced contamination in that area. Notably, the elevated Pb concentration at site 2 aligns with findings by Pikuła and Stępień (2021), who reported that Pb tends to accumulate in polluted soils due to its low mobility. Furthermore, the absence of Arsenic (As) at site 4 supports earlier observations that As distribution in soil is often highly localised and typically linked to specific contamination sources (Shrivastava *et al.*, 2015). This pattern highlights the potential environmental risk posed by Lead accumulation and underscores the need for further investigation into pollution sources and possible remediation efforts.

5.1.1 Ability of selected plants to absorb and accumulate Lead, Cadmium, Copper and Arsenic from contaminated soils

Across all study sites, *Cynodon dactylon* demonstrated significant heavy metal accumulation, particularly in its roots, which retained the highest concentrations of Lead (Pb) and Copper (Cu) at sites 1 and 2, respectively, as well as Arsenic (As) at site 2. In contrast, the plant accumulated lower levels of Cadmium (Cd) across different sites. This finding contradicts observations by Abdali Dehdezi *et al.* (2021), who reported that Cd accumulation in *C. dactylon* roots increased proportionally with rising Cadmium concentrations. The variation may be attributed to site-specific soil properties, such as pH, which influence metal bioavailability (Chibuike & Obiora, 2014). The elevated heavy metal levels at site 2 possibly originated from nearby industrial discharges and a garbage dumping site. The findings are consistent with Marchan (2015), who identified anthropogenic activities as primary sources of soil contamination.

At site 3, *Commelina benghalensis* roots accumulated the highest Pb concentrations, while *Pennisetum purpureum* shoots showed the highest Cd levels. Meanwhile, *Sida acuta* shoots at site 4 demonstrated significant Cd uptake. This is in line with previous findings that identified *S. acuta* as an efficient accumulator of Cd (Ogunkunle *et al.*, 2014). These patterns support earlier research suggesting species-specific efficiency in Cd phytoextraction (Asgari Lajayer *et al.*, 2019), which may be influenced by variations in root morphology and metal translocation mechanisms among plant species (Pinhey & Tebbs, 2022).

Interestingly, although As was the least abundant metal overall, *C. dactylon* shoots exhibited the highest As accumulation at sites 1 and 4. This aligns with findings by Khan *et al.* (2015), who noted that As uptake in plants can vary widely depending on soil composition and metal availability.

5.2 Wastewater sediment contamination

Sediments across all study sites demonstrated the capacity to absorb heavy metals from wastewater, with Lead (Pb) emerging as the most prevalent contaminant. The highest Pb concentration was recorded at site 2, followed by Copper (Cu), Cadmium (Cd), and Arsenic (As). The elevated Pb levels at site 2 may be attributed to its proximity to a nearby industrial area and a dumping site located along the Nakivubo channel. This observation aligns with findings by Duan *et al.* (2022), who reported that Pb is often the dominant contaminant in wetland sediments due to its strong adsorption affinity for organic matter and clay particles.

5.2.1 Ability of selected plants to absorb and accumulate Lead, Cadmium, Copper and Arsenic from wastewater sediments

Among the studied plant species, *Cynodon dactylon* consistently exhibited the highest accumulation of heavy metals, particularly Lead (Pb) in roots at sites 1 and 2, Copper (Cu) in roots at site 3, and Arsenic (As) in roots at site 2. These findings support its role as a reliable phytoremediator under varied environmental conditions (Song *et al.*, 2022). Similarly, *Commelina benghalensis* demonstrated substantial Pb accumulation at site 3, confirming earlier research by Gajbhiye and Hile (2020), which emphasised its effectiveness in extracting Pb from contaminated water sources.

In terms of Cadmium (Cd) accumulation, *Pennisetum purpureum* shoots had the highest Cd content at site 3, while *C. benghalensis* roots showed peak Cd accumulation at site 2. These results are consistent with findings by Zhou *et al.* (2020), who reported high Cd translocation in *P. purpureum*, reinforcing its potential as a phytoremediation candidate. Although *Sida acuta* had been recognized as a Cd accumulator in prior studies (Ashwathy & Krishnakumar, 2024), its uptake efficiency in this study was lower compared to the other species tested.

Arsenic was the least abundant metal across all sites, with the highest accumulation recorded in *C. dactylon* shoots at site 1 and *P. purpureum* roots at site 3. While both species showed some capacity for As uptake, their relatively low efficiency supports previous findings by Souri *et al.* (2017), which indicated that most plants accumulate As only to a limited extent unless they are specific hyperaccumulators. This suggests that arsenic content may have gradually built up over time rather than through active uptake.

Overall, the observed variability in heavy metal uptake across different plant species and sites indicates that phytoremediation efficiency is influenced by several interrelated factors, including metal bioavailability, environmental medium characteristics, and plant physiological traits (Yang *et al.*, 2017).

5.3 Mechanisms of phytoremediation by which plant species uptake Lead, Cadmium, Copper and Arsenic from soil and wastewater sediments

The primary phytoremediation mechanisms identified in this study were phytostabilisation and phytoextraction, assessed using the Bio-Concentration Factor (BCF), Translocation Factor (TF), and Biological Absorption Coefficient (BAC) (Nugroho *et al.*, 2021). A BCF greater than 1 suggested a plant's capacity to stabilise heavy metals within its roots, whereas BAC and TF values exceeding 1 indicated potential for phytoextraction (Ameh *et al.*, 2019). In soil, *Sida acuta* was found to be an effective phytoextractor of Pb and Cu, while *Cynodon dactylon* and *Pennisetum purpureum* were hyperaccumulators of Cd (Ullah *et al.*, 2020).

In wastewater sediments, phytostabilisation characterised by root uptake and metal precipitation within the rhizosphere was particularly evident in *C. dactylon* and *S. acuta*, aligning with findings by Stanislawska-Glubiak *et al.* (2015) and Lange *et al.* (2016), which emphasised the importance of

exclusion mechanisms in heavy metal tolerance. *C. dactylon* demonstrated strong phytostabilisation potential for Cu and As in sediments, corroborating Aslam *et al.* (2021), who reported that certain fast-growing plants efficiently absorb and store metals in their aerial tissues. Furthermore, the demonstrated ability of *P. purpureum* and *S. acuta* to phytoextract Pb and Cd from wastewater sediments highlights their potential application in bioremediation strategies.

A comparative analysis of heavy metal concentrations in soil and wastewater sediment samples across all test sites revealed that soils consistently contained higher levels of Pb, Cd, Cu, and As, resulting in greater metal accumulation in plant tissues. This observation agrees with Kinuthia *et al.* (2020), who noted that industrial wastewater discharged into open drainage channels contributes to the long-term buildup of heavy metals in soil. Similarly, Singh (2021) reported that wastewater irrigation and industrial runoff significantly elevate soil-metal concentrations, presenting long-term environmental risks. The observed metal accumulation trends suggest a common contamination source (most likely industrial effluents) as the primary contributor to heavy metal uptake in soils and plants (Zakaria *et al.*, 2021). The stronger retention of metals in soil, compared to their relatively lower presence in sediments, can be attributed to the soil's higher cation exchange capacity and greater organic matter content, which enhance metal binding and reduce leaching (Palansooriya *et al.*, 2020).

Overall, these results contribute to ongoing research on phytoremediation and reinforce the importance of selecting plant species with rapid growth, efficient metal transport systems, and enhanced detoxification capabilities as optimal candidates for heavy metal removal in contaminated environments (Aslam *et al.*, 2021; Nugroho *et al.*, 2021).

5.4 Limitations of the study

The study research took place in an open area where the final levels of heavy metals in soil, sediments from wastewater, and plant materials could be influenced by weather conditions. To prevent sudden fluctuations in the concentrations of Pb, Cd, Cu, and As, sampling was restricted to the dry season. Since the study area is located within the city, options for plant sampling locations were limited; thus, multiple samples (three or more) were randomly gathered from each of the four sites to compensate for this. Other potential sources of Pb, Cd, Cu, and As beyond industrial wastewater and solid waste might have also affected the heavy metal concentrations found in the plant materials, particularly noted at site 4.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Soils retained heavy metals more effectively than wastewater sediments, leading to prolonged metal availability for plant uptake. Industrial wastewater discharge is a major contributor to soil contamination.

Heavy metal contamination in soils varied by location, with Pb being the most prevalent at many sites, while Cu dominated at the control site. High levels of Pb, Cu, and Cd indicated ongoing pollution, primarily driven by industrial activities and inadequate waste management.

The effectiveness of phytoremediation was highly species-specific, with *C. dactylon* excelling at accumulating Pb, Cu, and As, while *C. benghalensis* and *P. purpureum* were more efficient for Pb and Cd accumulation, respectively. Selection of the right plant species based on the type of metal contamination for optimal remediation is therefore important.

Different plant species had varying capacities for phytoremediating heavy metals in wastewater sediments, with *C. dactylon* showing the most potential for Pb, Cu, and As accumulation, while *C. benghalensis* and *P. purpureum* were effective for Pb and Cd accumulation, respectively. The lower uptake of As by plants indicated potential limitations in its bioavailability or plant absorption efficiency.

S. acuta and *P. purpureum*, were effective at extracting Pb and Cd from contaminated environments, while *C. dactylon* excelled at stabilising Cu and As. The study plants have the potential for tailored phytoremediation strategies based on specific metal contaminants.

The success of heavy metal phytoremediation depended heavily on the choice of plant species and environmental conditions, and native wetland plants offered a sustainable, eco-friendly solution for remediating contaminated soil and wastewater sediments.

The study demonstrated that the selected plant species effectively accumulated significant amounts of Pb, Cd, Cu, and As, confirming their potential for use in the remediation of contaminated soils and wastewater sediments. The observed accumulation of heavy metals supports the use of phytostabilisation and phytoextraction as viable mechanisms for reducing heavy metal mobility and toxicity in polluted environments. These findings highlight the practical applicability of phytoremediation as an eco-friendly and cost-effective strategy for managing metal-contaminated sites and therefore the null hypotheses were rejected.

Phytoremediation was confirmed eco-friendly method for mitigating heavy metal pollution in soils and sediments, with *S. acuta*, *C. dactylon*, *P. purpureum*, and *C. benghalensis* demonstrating strong potential for effective application in both soils and wastewater sediments.

6.2 Recommendations

Targeted phytoremediation should be implemented using the most effective plant species identified in the study. *C. dactylon*, due to its superior accumulation of lead (Pb), copper (Cu), and arsenic (As), should be prioritised for use in areas with high concentrations of these metals. Its strong phytostabilisation potential for Cu and As also makes it ideal for preventing further metal leaching and dispersion. Similarly, *C. benghalensis* should be used in Pb-contaminated sites, while *P. purpureum* is recommended for cadmium (Cd) remediation, given its demonstrated efficiency in absorbing this metal.

Environmental monitoring programs should be established to regularly assess metal concentrations in both soils and wastewater sediments. This will help track the progress of phytoremediation efforts and ensure timely adjustments. Since soil retains heavy metals longer than sediments, emphasis should be placed on long-term soil monitoring and the periodic assessment of metal bioavailability. In addition, policymakers and environmental agencies should consider integrating phytoremediation into wetland restoration and industrial waste management plans. Encouraging the use of native plants for environmental cleanup offers a sustainable, low-cost alternative to conventional remediation methods and enhances biodiversity conservation.

Community awareness and involvement should be promoted. Local stakeholders can play a vital role in supporting phytoremediation initiatives through planting, maintenance, and monitoring activities, contributing to long-term environmental stewardship and public health protection.

6.2.1 Suggestions for further research

A study should be done to assess the potential of phytoremediation of heavy metals like Lead, Cadmium, Copper and Arsenic from irrigated agriculture soils using other plants, especially weeds, since there is a possibility of using contaminated water for irrigation from our water sources.

Research should be done to evaluate the potential of phytoremediation using *C. benghalensis*, *P. purpureum*, *S. acuta* and *C. dactylon* to remove heavy metals such as Mercury, Selenium, Chromium and Nickel from wastewater sediments and soil in Nakivubo wetland. This is because these heavy metals are possibly from the same sources as the present study metals.

The potential of study plants for phytoremediation of different and specific heavy metals at different activity sites, like mining sites, should be assessed since these plants proved to be good accumulators of different heavy metals at different contaminated sites.

Further research should investigate the environmental factors influencing metal uptake, including soil pH, organic matter content, and metal speciation. Understanding how these factors influence plant uptake will help optimise phytoremediation strategies and potentially improve the performance of selected plant species under varying site conditions.

More research into long-term performance and field (*ex-situ*) applications of *C. benghalensis*, *P. purpureum*, *S. acuta*, and *C. dactylon* is suggested to optimise remediation efficiency.

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APPENDIX

Appendix 1: Soil sampling by site

Site	Number of composite samples	Sample collection location	Distance from channel (m)	Sampling depth (cm)	Equipment used
1	3	Around the plant roots	0.5	5-10	Trowel, auger
2	4	Around the plant roots	0.5	5-10	Trowel, auger
3	4	Around the plant roots	0.5	5-10	Trowel, auger
4	4	Around the plant roots	500 (control site)	5-10	Trowel, auger
Total	15				


Appendix 2: Wastewater sediments sampling by site

Site	Number of composite samples	Sample collection location	Sampling depth (cm)	Equipment used
1	3	Channel shore	5-10	Trowel, plastic container
2	4	Channel shore	5-10	Trowel, plastic container
3	4	Channel shore	5-10	Trowel, plastic container
Total	11			

Appendix 3: Plant sampling by site and substrate

Site	Substrate	Plant species collected	Number of plant samples
1	Soil	<i>Commelina benghalensis, Sida acuta, Cynodon dactylon</i>	9
	Wastewater sediment	<i>Commelina benghalensis, Sida acuta, Cynodon dactylon</i>	9
2	Soil	<i>Commelina benghalensis, Sida acuta, Cynodon dactylon, Pennisetum purpureum</i>	12
	Wastewater sediment	<i>Commelina benghalensis, Sida acuta, Cynodon dactylon, Pennisetum purpureum</i>	12
3	Soil	<i>Commelina benghalensis, Sida acuta, Cynodon dactylon, Pennisetum purpureum</i>	12
	Wastewater sediment	<i>Commelina benghalensis, Sida acuta, Cynodon dactylon, Pennisetum purpureum</i>	12
4	Soil	<i>Commelina benghalensis, Sida acuta, Cynodon dactylon, Pennisetum purpureum</i>	12
	-	-	
			Total = 78

Appendix 4: Introductory letter


KYAMBOGO UNIVERSITY
P. O. BOX 1 KYAMBOGO
Tel: 041 - 4286792 Fax: 256-41-220464
Website :www.kyu.ac.ug, Email: drgt@kyu.ac.ug
Directorate of Research and Graduate Training
Office of the Director

Date: 19th June, 2023

TO WHOM IT MAY CONCERN

RE:AKATUKUNDA ROSELYNE.....

Dear Sir/Madam,

This is to introduce to you the above named student Reg: No2114/GMSM/18992/PE.....pursuing Master of Science in Conservation and Natural resource Management Department ofBiological Sciences....., Kyambogo University.

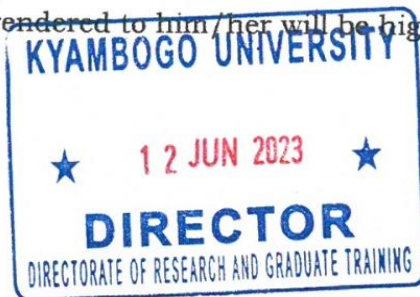
She/he intends to carry out research on Potential of Selected plant species for Phytoremediation of heavy metals in soil and wastewater sediments from Naxivubo wetland, Uganda in partial fulfillment of the requirements for the award of the degree of Master of Science in Conservation and Natural Resource management of Kyambogo University

The purpose of this letter therefore is to request you to grant him/her permission to carry out his/her study in your institution.

Any assistance rendered to him/her will be highly appreciated.

Yours sincerely,


Prof. Bosco Bua
AG. DIRECTOR



Appendix 5: A – Study site, B – Collection of samples, C – Packing and labelling, D – Plant sample cleaning, E – Weighing of dry samples, F – Sample digestion, G – Sample analysis (AAS).

