Blueprint Academic Publishers

Journal of Aquatic and Terrestrial Ecosystems
Journal ISSN: 2960-1118
4(2)
Received: March 14, 2026
Accepted: April 30, 2026
Published: May 14, 2026

Bioremediation Potential of Actinobacteria in Heavy Metals Contaminated Soils in Kipkenyo Dumpsite, Eldoret, Kenya

Kipsiro C. Klara, Kipkorir K. G. Kiptoo and Wanjohi Lucy

Department of Environmental Sciences, School of Environmental Sciences and Natural Resources Management, P.O Box 1125-30100, Eldoret, Kenya

Abstract

Contamination of soils by potentially toxic elements poses significant environmental and health hazards globally, especially in mismanaged waste disposal sites. This is due to deposition of solid and liquid substances in the dumpsites and industrial pollutions into the soil which form toxic chemicals as well as evaporation of harmful gases into the atmosphere. This study assessed the bioremediation potential of Actinobacteria in heavy metals contaminated soils in Kipkenyo dumpsite, Eldoret, Kenya. Initial concentrations of Cadmium, Cobalt, Chromium, Copper, Nickel, Iron, Manganese and Zinc were quantified using atomic absorption spectrophotometry. The dumpsite soil samples were characterized to identify the species of bacteria present. The most abundant species were isolated, cultured and used as a positive control in the bioremediation experimental set up. The isolated bacteria were identified using morphological characteristics and biochemical tests using Bergy's manual of determinative bacteriology. *Streptomyces spp.* was isolated and cultured from soil samples from the University of Eldoret arboretum. The data was analyzed using R programming language version 4.4.2. The initial concentrations of heavy metal elements in Kipkenyo dumpsite soil samples had significant variations ($P< 0.05$). The final concentrations of elements also showed significant changes in samples treated with either *Streptomyces spp*. or *Bacillus spp* compared to that of negative control. *Bacillus spp.* was the most abundant in the dumpsite soil samples. Zinc had a higher degradation percentage (82.68% in *Streptomyces spp.* and 80.68% in *Bacillus spp*.) while chromium had the least percentage degradation (6.49% in *Streptomyces spp.* and 10.39% in *Bacillus spp*.). *Streptomyces spp.* had a higher percentage degradation in most heavy metal elements compared to *Bacillus spp.* These findings underscore the potential use of native actinobacteria in bioremediating heavy metal-contaminated soils and serve as a basis for creating environmentally friendly dumpsite rehabilitation techniques.

Keywords: Heavy Metals, Dump Sites, Bioremediation, Actinobacteria

Correspondence: klarachepsy@gmail.com

Copyright © 2026 Kipsiro et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY).

Funding: The author received no financial support for the research, authorship and/or publication of this article.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials or upon reasonable request.

Competing interests: The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article

Introduction

The ecosystem and human health are at risk of heavy metals contamination due to their persistence and bioaccumulation (Roy et al., 2022). The aquatic, terrestrial, and atmospheric environments are negatively impacted by heavy metal pollution, which can be man-made or natural in origin and is not readily degradable (Hembrom et al., 2020). Among the major elements of biological toxicity found in soil are mercury (Hg), cadmium (Cd), lead (Pb), chromium (Cr), arsenic (As), and others. Other heavy metals with specific biological toxicity are also included, notably vanadium, stannum (Sn), nickel (Ni), copper (Cu), and zinc (Zn) (Mai et al., 2025). A major threat to plant life, human health, and the world's food supply is heavy metal (HM) contamination of agricultural soils. Crop health and yield are negatively affected by hazardous levels of HM in agricultural soils (Angon et al., 2024). There are numerous recognized sources of hazardous metals, including the earth, which releases them into food, air, and water, as well as human activities including fertilizer application in agriculture, pesticide and herbicide use, and irrigation (Alengebawy et al., 2021).

Heavy metals can also come from industry, cigarette smoking, paints, sewage, and waste disposal, as well as from automotive emissions (Onakpa et al., 2018.) The issue has been exacerbated by extensive infrastructure development, rising car density, and general lifestyle changes, particularly in developing countries, which have increased point and diffuse sources of metal emissions (Kumar et al., 2017). These metals begin to build up in the food chain and bioaccumulate in the systems of animals and humans once they enter into the water and soil, leading to a number of conditions like cancer and Minamata (chronic mercury poisoning) (Daripa et al., 2023). Higher concentrations of metal elements damage the environment, which has negative effects on plant, animal, and human health. Due to their toxicity and the presence of carcinogenic metalloids, toxic metals can cause diabetes, cardiovascular ailments, neurotoxicity, urinary tract disorders, and skin and lung cancer (Okereafor et al., 2020).

Numerous remediation techniques have been researched and can be categorized into two groups: those that eliminate contaminants and those that fixate, oxidize, or otherwise change pollutants into harmless forms (Najim et al., 2024). These technologies for cleanup can be implemented on-site or off-site, employing three different types of remediation treatments: chemical, physical, and biological methods (Zaghloul & Saber, 2019). Traditional techniques for remediating heavy metal-contaminated

soil have been employed for decades and have produced excellent results, but they also have drawbacks (Sharma et al., 2018). The chemical and physical methods, when applied alone, typically produce by-products and are not cost-effective (Díaz et al., 2024). Traditional remediation techniques are not appropriate or economical, since they may bring about more environmental health risks instead of providing a remedy (Gunjyal et al., 2023). This study adopted the indigenous strains that are already pre-adapted to the Kipkenyo environment for heavy metals bioremediation.

Microorganisms have the capacity to detoxify, degrade, and even bioaccumulate toxic organic as well as inorganic compounds (Medfu Tarekegn et al., 2020). Numerous microbial strains have been successfully used to remove heavy metals, and the biotechnological use of microorganisms is still being developed (Volarić et al., 2021). Bioremediation using the actinobacteria is arising as alternative heavy metals cleaning technique because it's an environment friendly approach achieved through natural processes (Choudhary et al., 2017). One of the key features of Actinobacteria is their distinctive and highly complex cell wall structure, which greatly improves their ability to biosorb metal(loid) ions. Their cell envelope consists of a thick peptidoglycan layer connected with teichoic acids, lipids, and surface proteins, and in some genera such as *Rhodococcus*, it also includes hydrophobic mycolic acids (Presentato et al., 2020). This intricate architecture creates a large number of reactive functional groups on the cell surface, such as hydroxyl (OH^-), carboxyl (COO^-), carbonyl (CO), phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), and amino (NH_2^+/NH_3^+) groups (Jantschke, 2022). These sites actively bind metal(loid) ions through ion exchange, complex formation, and electrostatic attraction.

In addition to their surface chemistry, Actinobacteria possess metabolic traits that further boost biosorption performance. They can produce extracellular polymeric substances (EPS), siderophores, and redox-active metabolites, all of which enhance metal chelation and immobilization (Verma et al., 2025). Their strong respiratory capacity and stress-response mechanisms also help them maintain cellular balance even under high metal stress, allowing biosorption to continue over extended periods (Behera & Das, 2023).

Within this phylum, genera such as *Streptomyces*, *Arthrobacter*, and *Rhodococcus* are especially noted for their strong metal resistance and biosorption abilities (Timková et al., 2018). This is largely due to their adaptable cell envelope structures and flexible regulatory systems, which together optimize metal binding, sequestration, and detoxification in harsh environmental conditions (Hashim et al., 2026). Actinobacteria are able to live in a wide range of extreme environments, including very high or very low temperatures, highly salty conditions, strongly acidic or alkaline pH levels, intense pressure, and very dry habitats. Their survival is mainly due to strong adaptive features, especially the stability of their proteins, which is supported by a specialized amino acid composition. This structural stability enables their cells to remain functional under environmental stresses that are lethal to most other microorganisms (Yaradoddi & Kontro, 2021).

Heavy metal biosorption from aqueous solutions has demonstrated great potential, with notable benefits including affordable, low cost, availability, profitability, convenience of use, and high efficiency particularly when working with

low concentrations (Javanbakht et al., 2013). Many microorganisms, including bacteria, yeast, algae, protozoa, and fungi, have developed defense mechanisms against heavy metal toxicity, including adsorption, oxidation, reduction, methylation, and absorption (Abd Elnabi et al., 2023). Additionally, it was discovered that some bacteria can create chelating compounds that bind metals and lessen their toxicity while simultaneously using mechanisms of tolerance and detoxification of heavy metals (Pal et al., 2022). Numerous live microorganisms have been reported to decrease or change harmful substances into less harmful forms (Nanda et al., 2019).

Kipkenyo dumpsite in Eldoret, Kenya faces intensive pollution from municipal waste, agricultural waste, industrial, E-waste and construction and demolition waste in Uasin Gishu county. The dumpsite's close proximity of about 310m to River Sosiani and the nearby residential settlements raises significant environmental and public health concerns. A previous study by Naitore, (2018) in Uasin Gishu reported that the spatial distribution of heavy metals in River Sosiani suggested that there are concentrations of heavy metals within the vicinity of the dumpsite under anthropogenic influence. According to the modeling outputs, the Kipkenyo dumpsite is responsible for the presence of high concentrations of zinc, copper, and lead, owing to the leakage of toxic substances from the waste area into the river system This study is therefore critical to policy makers as it highlights the importance of bioremediation using the Actinobacteria in Kipkenyo dumpsite to reduce the exposure risks to the neighboring communities. Though the potential of various microbes has been explored, the indigenous Actinobacteria of the Kipkenyo dumpsite remain largely uncharacterized. This study seeks to isolate, identify, and evaluate the bioremediation potential of these strains to provide a localized, cost-effective solution for soil restoration.

Materials and Methods

Description of the Study Area

The research was conducted in Uasin Gishu County, one of Kenya's 47 counties. The county borders Trans Nzoia County to the north, Kericho County to the south, Baringo and Elgeyo Marakwet counties to the east, and Nandi and Kakamega Counties to the west. Kipkenyo dumpsite is located in Kapseret sub-county, Uasin Gishu county in the outskirts of Eldoret city. It is approximately 2km from Eldoret city. Its geographical coordinates are 0°52'18'.50''N, 35°23'92.83'E, with elevation of 2100 meters. The dumpsite covers an area of approximately 2.996 hectares.

Climatic Conditions

The climate in Uasin Gishu County is warm and temperate (Beth & Jamal, 2023). Uasin Gishu has high, reliable rainfall averaging between 900mm and 1400 mm (Nyongesa et al., 2023). The rainfall is experienced in March to September, with two peaks in May and August. Due to the high altitude in the area, temperatures are relatively low ranging from 12°C in July to 23°C in March (Murgor, 2021). The average temperature in the area is 18°C during the wet season with a maximum of 26.1°C during the driest season (February) and a minimum of 8.4°C in the coolest season in June (Jepkoech, 2013).

Human and Economic Activities

Eldoret Town, in particular, is an epicenter of commercial activity in Uasin Gishu County (Carter, 2023). The major activities undertaken involve catering,

wholesales, motor vehicle repair / sales, retail shops, groceries and banking. Eldoret is also a major industrial center hosting mainly agro-based industries and related secondary industries. These include steel rolling mills, paper board mills, plywood/chipboard mills, sawmills, textile mills, wheat mills, milk processing facilities, and wood preservation facilities, among others. All solid waste from the commercial places are disposed of either by privately licensed garbage collectors or the Uasin Gishu county administration (Cherogony, 2018). The Kipkenyo dumpsite receives all of the county's waste, putting the nearby communities at risk for respiratory problems, cancer, and gastrointestinal issues.

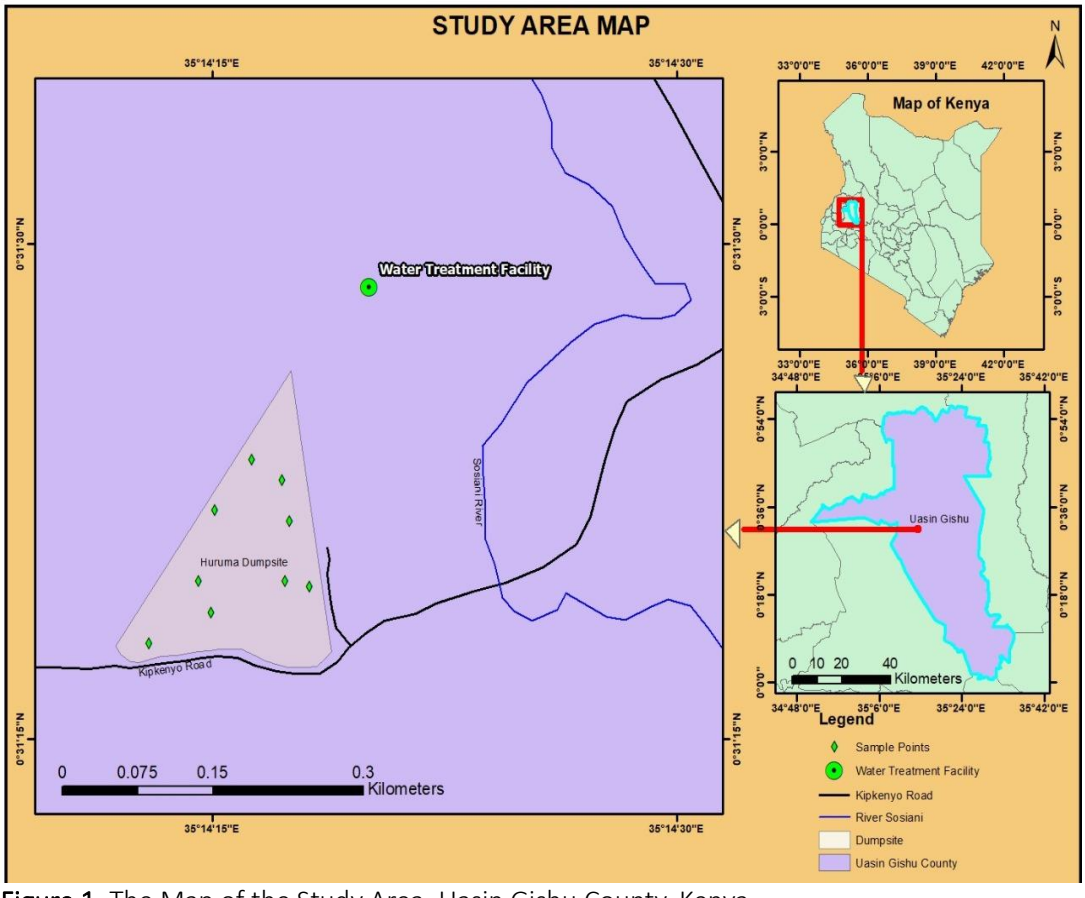

Figure 1. The Map of the Study Area, Uasin Gishu County, Kenya

Research design

The soil samples used in the study were collected from Kipkenyo dumpsite in Eldoret municipality, Uasin Gishu County, Kenya. Fresh soil from the University of Eldoret Arboretum was sampled for isolation and culturing of Actinobacteria (*Streptomyces spp*). The soil from the University of Eldoret Arboretum was selected as a source of *Streptomyces spp.* because it has relatively undisturbed conditions, a high organic matter content, and minimal human disturbance, all of which support a rich abundance and diversity of Actinobacteria. To ensure a comprehensive coverage of the study area, the site was divided in to four sections, each representing different microhabitats. Within each section, a random sampling approach was employed. All soil samples were then placed in a sterile bag, labelled, and

transported to the University of Eldoret Laboratory for sample preparation and analysis.

Biodiversity of Bacteria in Kipkenyo Dumpsite

Soil Sample Preparation

A series of dilutions up to 10-10 were applied to the dumpsite soil sample. 10mls of distilled water were mixed with 1g of each soil sample, and the mixture was thoroughly stirred until it dissolved. Ten test tubes were prepared and labeled as 10^{-1},10^{-2},10^{-3}...Up to 10^{-10}. Each test tube was filled with 9 mls of distilled water. 1 ml of the original sample was extracted, put into the first tube (10-1) and thoroughly mixed. 1 ml of the 10-1 dilution was obtained and put in the subsequent test tube (10-2). After thorough mixing, the dilution was carried out step-by-step till it reached 10-10.

Media Preparation Procedure

Based on the manufacturer's recommendation, 5.6 g nutrient agar in 200 ml distilled water was sterilized by autoclaving at 121 °C for 15 minutes and cooled to 45 °C. Agar, mineral salts, casein, and starch were dissolved in 1 L of distilled water to prepare the starch-casein medium, which was then sterilized for 15 minutes at 121 °C in order to isolate *Streptomyces spp*.

Isolation, Characterization and Identification of Bacteria In Dumpsite Soil

Characterizing the soil samples collected from the dumpsite allowed for the determination of the type of bacteria present. In order to compare the bacterium's capacity to bioremediate with that of *Streptomyces spp.,* the most common species of bacteria was isolated and cultured to act as the positive control in the bioremediation study. Nutrient agar medium was sterilized, put on petri dishes, and let to solidify. A sterile glass spreader was used to evenly distribute 0.2 ml of the serially diluted sample of 10^{-10} onto the solidified medium. Inoculated plates were incubated for 24 hours at 25°C in an upside-down position. Streak method was used in the subculturing process (Jain et al., 2020). To obtain pure cultures, sterile wire loops were used to select single colonies, which were then streaked on sterile media. Bergey's manual (gram staining, catalase and protease test) of determinative bacteriology was used to identify the isolated bacteria through physical characterization and biochemical testing (Holt, 1994). The most abundant bacteria were *Bacillus spp.* To culture the *Bacillus spp*. for use as a positive control in bioremediation, the colony was streaked on fresh plates with nutrient agar media that had been sterilized (Harun et al., 2023). *Bacillus spp.* was harvested and stored in nutrient broth.

Relative abundance was calculated using the following formulae:

$$\textit{Relative Abundance}\ (\%) = \left(\frac{\text{Colony forming units (CFUs)}\textit{ of a species}}{\text{Total colony forming units}}\right) X\ 100$$

Culturing of Actinobacteria (Streptomyces spp.) in Starch Casein Agar

Soil samples from the arboretum that were serially diluted were cultured using the spread plate technique. Starch Casein Agar medium that had been sterilized and cooled was aseptically transferred into eight petri dishes and left to solidify. After preparing samples in dilutions ranging from 10^{-7} to 10^{-10}, 0.2 mL of each diluted sample was aseptically put onto the solidified agar's surface. A sterile glass spreader was used to ensure consistent distribution of the inoculum. The petri dishes were properly labeled, parafilm-sealed, and incubated upside down at 26°C for seven days under

conventional aerobic conditions. After incubation, the development of microorganisms was monitored and analyzed.

Sub Culturing

Morphological observations were made following seven days of incubation. In order to confirm that Actinobacteria (*Streptomyces spp.*), colonies were subjected to Gram staining and microscopic analysis, catalase test., methyl red test,starch hydrolysis and protease test. Sterilized starch casein agar was streaked with a representative colony of the Actinobacteria group aseptically to make sub-culturing easier. The inoculated petri dishes were incubated for four days at 26°C in an aerobic environment to encourage additional growth, isolation and stocking in nutrient broth for bioremediation.

Experimental Set Up

Experimental design technique was employed as it involved adding treatment to subject, that was addition of *Streptomyces spp.* and *Bacillus spp.* in samples of contaminated dumpsite soils.
The experiment consisted of 3 treatments namely;

i. Group A: Sterilized dumpsite soil + *Streptomyces* spp.
ii. Group B (Positive control): Sterilized dumpsite soil + *Bacillus* spp.
iii. Group C (Negative control): Sterilized dumpsite soil + distilled water only (no bacterial inoculation)

Each treatment was set up in five replicates, and the experiment ran for 100 days.

Laboratory analysis

The soil samples were sieved to remove debris before analysis of Iron, Zinc, Copper, Manganese, Chromium, Cadmium, Nickel and Cobalt.

Digestion of the soil samples for heavy metal analysis

The soil samples were dried for 24 hours at 70°C in an oven. Using a pestle and motor, the dried soil samples were ground into smaller particles. The fine soil samples were sieved using a sieve of mesh size 2mm. A clean digestive tube was filled with 0.3g of the dry materials after they had been weighed. This process was repeated until eight digestion tubes, one for each element under analysis, were filled. 0.42 grams of selenium powder were measured to create the digestion mixture, which was then put into a digestion flask. The digesting flask was then filled with 420 milliliters of sulfuric acid, 350 milliliters of 30% hydrogen peroxide, and 14 grams of lithium sulphate, all of which were thoroughly mixed. A similar technique was applied by (Okpa et al., 2024).

Following that, two reagent blanks for each batch sample and 4.4 ml of the digestion mixture were added to each tube. The samples were subsequently placed in digestion blocks and heated for two hours at 360°C using a heating block. The solution was allowed to cool and then filtered using 0.45µm Whatman filter paper. Each clear solution that was produced was diluted with fifty milliliters of distilled water, thoroughly mixed, and then left to settle. The AAS ran the clear solution.

Atomic adsorption spectrophotometer Analysis

Heavy metal analysis was done using AAS. Based on the experimental setup, five replicates were used to determine the metals' initial and final concentrations. The working solutions were diluted in series to provide a set of standard solutions with known concentrations of Zn, Fe, Mn, Co, Cu, Cr,

Cd, and Ni for instrumental calibration. For each metal, a 1000 mg/l stock solution comprising ions of iron, zinc, copper, manganese, chromium, cadmium, nickel, and cobalt was prepared independently. They were made by dissolving in distilled water 1.907g of zinc (II) chloride, 2.67g of copper sulphate, 1g of manganese nitrate, 3.05g of chromium (III) nitrate, 2.1g of cadmium nitrate, and 2.103g of nickel nitrate. A calibration curve was plotted using standard solutions of 0, 1, 2, 3, 4, and 5 mg/L for each metal ion, and their absorbance values were measured using AAS. In addition to using a blank for baseline correction, a Certified Reference Material (CRM) which was analyzed under the same conditions as the samples was included to verify the accuracy and reliability of the AAS measurements, ensuring the calibration results were traceable and valid. The absorbance was then plotted against the concentration of each metal to create a calibration curve.

Deionized water served as the blank sample used to zero the AAS device. To generate a linear calibration curve, each standard was aspirated, and the absorbance was noted. The metal concentration of the unknown samples was then determined by comparing them to the curve. Each metal was evaluated using a specific hollow cathode lamp (HCL) in the AAS. The light from the lamps had distinct wavelengths that the metal atoms absorbed. Basing on the metal being examined, the lamps were changed to tally with the metal under analysis. Before the examination, each lamp was warmed up for stability. The Table 1 below shows the wavelengths of different metals and the lambs used for various heavy metals analysis.

Table 1: Showing wavelength of each metal and the lamp used during heavy metals analysis

Metal	Zinc	Nickel	Iron	Chromium	Cadmium	Manganese	Cobalt	Copper
Wavelength	~213.9	~232.0	~248.0	~357.0	~228.8	~279.5	~240.7	~324.8
Lamp used (HCL)	Zn	Ni	Fe	Cr	Cd	Mn	Co	Cu

Bioremediation of Heavy Metals

Bioremediation of heavy metals was carried out using a method by Fauziah et al. (2017) on their research on bioaugmentation potentials of individual isolates from landfill on metal polluted soil with slight modifications. To ensure that only the introduced bacteria aided in the remediation process, dumpsite soil samples were sterilized to eliminate indigenous microbial competition. In this study, there were three treatments used in the trial; treatment A involved treating or inoculating the dumpsite soil samples with *Streptomyces spp*., treatment B involved treating the dumpsite soil samples with *Bacillus species* (positive control), and treatment C involved the absence of any bacterial treatment (negative control). Five replicates of each treatment were used in the experiment. *Bacillus spp*. which was a treatment B, served as the experiment's positive control, and treatment C served as its negative control. Five containers containing 200g of sterilized dumpsite soil samples and 200ml of distilled water each were included in each treatment to moisten the soils. *Streptomyces spp*. (1×10^7 CFU/ml) and *Bacillus spp*. (1×10^7 CFU/ml) were added to treatment A and treatment B, respectively. Treatment C received no treatment. The samples were properly labeled and kept safe from

contamination by a parafilm covering that allowed for aeration. The treatment was placed on a shaker set at 25°C and 100 revolutions per minute for 100 days. After 100 days, degradation potential was calculated as follows:

$$\text{Efficiency (\%)} = \left(\frac{Ci - Cf}{Ci}\right) \times 100\%$$

Where Ci is the initial concentration and Cf is the final concentration of the heavy metals.

Data analysis

R programming language version 4.4.0 was used in the data analysis. Shapiro-Wilk test at alpha=0.05 was used to assess the data for normality. A one-way ANOVA was conducted to compare the means among the different heavy metals' concentrations; a Tukey HSD test was done to rank the means of the different groups.

Results and Discussion

Heavy Metals Concentration

Soil samples from the Kipkenyo dumpsite in Eldoret municipality, Kenya, were examined for the concentrations of various heavy metals. The elements analyzed include Cadmium (Cd), Cobalt (Co), Chromium (Cr), Copper (Cu), Iron (Fe), Manganese (Mn), Nickel (Ni), and Zinc (Zn) as shown in Table 2. The results of the heavy metals concentration are indicated in Table 2 below. There were statistically significant differences between the concentrations of the metals ($p < 0.05$). Iron, manganese, and zinc had higher concentrations than cobalt and cadmium. Iron (Fe) had the highest concentration, with a mean of 25.25 ± 0.05 mg/kg probably due to diverse range of anthropogenic iron from waste materials such as discarded iron cans, vehicle parts, electronic components and construction debris disposed in the dumpsite (Agbeshie et al., 2020). Park et al. (2018) reported a high concentration of Fe and associated it with the high mobility of Fe metals. High levels of iron are also attributed to the high residual iron concentration in soils due to its high abundance in the earth crust and it is also concentrated during pedogenic weathering into stable iron-oxides minerals (Owonubi, 2020). Despite iron's critical function in plant and microbial nutrition, it can interfere with the uptake of other vital minerals and produce oxidative stress in plants when it is present in excess (Harish et al., 2023). Manganese (Mn) had the second highest concentration of 3.12 ± 0.01 mg/kg (Table 2). The WHO (2008) states that in order to prevent phytotoxic effects, manganese levels in agricultural soils should not be higher than 1.80 mg/kg. This means that the levels reported in this study are higher than the safe limit and may affect microbial balance and plant growth. The high manganese levels are attributed to high waste disposal of metallic wastes such as batteries, electronics, steel, and manganese rich wastes (alloys) which leach in to the soil gradually (Naseri et al., 2022). Higher levels of Mn also lead to toxicity to the microbiome due to disruption of enzymatic activities, cell membrane damage, and oxidative stress as this creates a harsh environment that only resilient strains like Actinobacteria can survive (Dey et al., 2023). The zinc (Zn) level was found to be 1.00 ± 0.01 mg/kg (Table 2), which is within the safe limit as per NEMA guidelines (NEMA, 2006), which suggest that agricultural soils should contain not more than 5.0 mg/kg. A study based on literature review on heavy metal accumulation in crops also found zinc levels within the permissible limits (Chabukdhara et al., 2021). Chromium (Cr) also showed notable presence (0.77 ± 0.00 mg/kg), which implicated a higher concentration as compared with the WHO permissible limit of 0.1 mg/kg for Cr in

soils, particularly in oxidized forms. Copper (Cu) concentration was at 0.32± 0.00 mg/kg (Table 2), its presence could be due to deposits of metal scraps and organic residues. This concentration was significantly lower than the recommended safety limit (50-100 mg/kg). Nickel (Ni) concentration was at 0.24± 0.00 mg/kg, which was within NEMA's allowable limits of 40 mg/kg in soils, but elevated concentrations even within recommendable limits can still be toxic to soil microorganisms and plants. These findings concur with Hassan et al., (2019) who noted that nickel has the potential to reduce seed germination, root and shoot growth, biomass accumulation, and final crop production. Moreover, Ni toxicity also causes chlorosis and necrosis and inhibits various physiological processes (photosynthesis, transpiration) and cause oxidative damage in plants (Ameen et al., 2019). Cadmium (Cd) concentration was at 0.06± 0.00 mg/kg. WHO (2008) and NEMA (2006) recommend maximum allowable concentrations of 0.01–0.05 mg/kg for Cd in soil and water. Cadmium levels in Kipkenyo dumpsite soil significantly exceeded safe limits possibly due to waste types like batteries, plastics, and pigments. Cadmium is a known carcinogen and poses serious risks even at low concentrations due to its high mobility and bio-accumulative nature (Shetty et al., 2025). A study by Satarug et al. (2022) found out that higher levels of cadmium pollution were as a result of volcanic emissions, biomass and fossil fuel combustion, and cigarette smoke. Cobalt (Co) was recorded at 0.06 ± 0.00 mg/kg. The WHO (2008) recommends a limit of 0.1-0.2 mg/kg for cobalt. The low concentration of cobalt in Kipkenyo dumpsite was probably due to a lower volume of cobalt-containing waste such as rechargeable batteries and metal alloys.

Table 2: The mean concentrations of the heavy metals and their standard errors (SE) in Kipkenyo dumpsite

Metals	Observed concentration	WHO limits	Interpretation
Cadmium	0.06±0.00	0.01-0.05mg/kg	Above limits-Toxic and carcinogenic
Cobalt	0.06±0.00	≤0.2 mg/kg	Within limits
Chromium	0.77 ± 0.00	0.05-0.10 mg/kg	Above limit-toxic
Copper	0.32± 0.00	≤36mg/kg	Within limits
Iron	25.25 ± 0.05	>2000mg/kg	Within limits
Manganese	3.12 ± 0.01	≤1.80mg/kg	Above limit-phytotoxic
Nickel	0.24± 0.00	≤ 40mg/kg	Within limits
Zinc	1.00± 0.01	≤300 mg/kg	Within limits

Bacteria species abundance in Kipkenyo dumpsite

Numerous species were found in the dumpsite soil samples with *Bacillus species* being the most abundant. Six bacterial species were identified in the dumpsite soil samples. These included: *Escherichia coli (E. coli), Pseudomonas species, Staphylococcus species, Streptococcus species*, and *Arthrobacter species*. Colony-forming unit (CFU) counts were used to calculate the relative abundance of each species. *Streptomyces* species were not detected among the bacterial isolates from the dumpsite soil samples; they were instead isolated from arboretum soil and subsequently used in bioaugmentation experiments to evaluate their potential in soil remediation. *Bacillus species* was the most abundant with 35.55% (Figure 2), probably due to their ability to form endospores that enables

them to be highly resistant and able to thrive in harsh, nutrient rich and heavy metals contaminated soils (Fakhar et al., 2022). The next abundant bacteria were *E. coli* (20%) (Figure 2). Their presence may be attributed to continuous disposal of fecal and animal waste coupled with nutrient rich environment created by decomposing organic materials (Liyanage et al., 2024). *Pseudomonas species* had an abundance of (15.5%), they are capable of surviving in dumpsite conditions due to their exceptional metabolic versatility, heavy metals tolerance and the ability to degrade organic pollutants (Karadžić et al., 2021). Their capacity to form biofilms protect them from harsh environmental stress such as high UV rays exposure (Pezzoni et al., 2022). The presence of potential pathogens like *E. coli* and *Staphylococcus species*, suggests that dumpsite contamination may pose health and environmental hazards (Addy et al., 2023). A study by Adekanmbi et al. (2024) on solid waste dumpsite leachate and contiguous surface water found out that *E.coli* in dumpsites have potential of causing a public health threat. The primary health effects of the most prevalent bacterial contaminants are infections in immunocompromised individuals and hospital-acquired infections (Gohad & Bhendarkar, 2025). These bacterial contaminants include *Escherichia coli*, *Pseudomonas aeruginosa*, *Staphylococcus* species, *Staphylococcus aureus*, and *Micrococcus luteus* (Monteiro et al., 2022). Figure 2 presents a detailed breakdown of the bacterial species composition and their relative abundances.

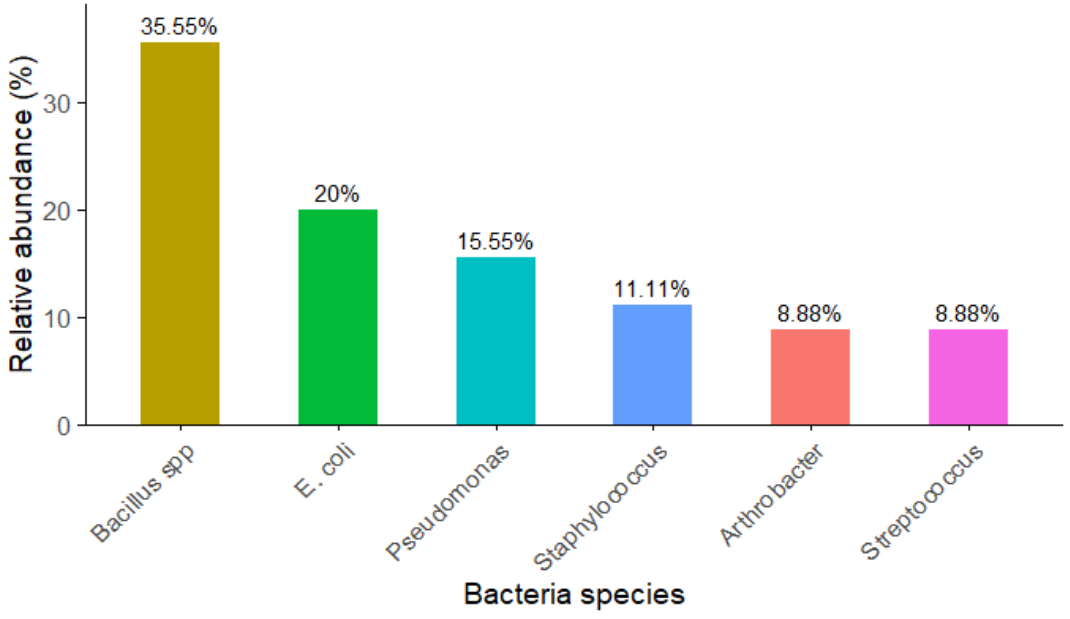

Figure 2: Relative abundance of the six identified species in Kipkenyo dumpsite soil sample

Efficiency of selected Bacteria in bioremediation of heavy metals

Bioremediation is one of the best methods adopted to alleviate heavy metal pollution due to its sustainability and cost-effectiveness (Abo-Alkasem et al., 2023). It relies on bacteria, microbes and plants (Sreedevi et al., 2022). Figure 3 below shows the percentage degradation that has been attributed to either *Streptomyces spp.* and *Bacillus spp*. minus the external factors. In the negative control (Treatment C), where no bacterial inoculation was applied, metal concentrations showed no substantial change over the 100-day period. Only

minimal reductions were observed, which can be attributed to natural attenuation processes such as slight leaching and environmental settling effects, rather than microbial activity. Zinc had the highest degradation percentage with *Streptomyces spp.* degrading 82.68% and *Bacillus spp* 80.68% (Figure 3). These findings agree with Kumari et al. (2023) who noted that *Streptomyces spp.* had a high degradation percentage for Zn^{2+} and Pb^{2+} from an aqueous solution. Copper followed closely with *Streptomyces spp*. having a degradation percentage of 78.15 and *Bacillus spp.* 68.75. These findings agreeC with Boke Ozkoc et al. (2023) who concluded that S. griseus and Bacillus spp. are good options for bioremediation of copper ions from polluted environments. The higher efficiency of *Streptomyces* spp. in the removal of Zn and Cu compared to *Bacillus* spp. may be attributed to their complex cell wall structure, which contains chitin-like compounds, glucans, and various functional groups such as hydroxyl, carboxyl, and amino groups that enhance metal binding through biosorption. In contrast, the relatively higher performance of *Bacillus* spp. in the removal of Ni, Fe, and Cr may be due to their ability to produce diverse siderophores iron-chelating compounds that facilitate the uptake of Fe and similar metals as well as their metabolic versatility, which enables processes such as bioaccumulation and redox transformation, particularly in the case of chromium. Cadmium and Cobalt showed equal degradation percentage where in both cases *streptomyces spp* accounted for 50% degradation and *Bacillus spp* was responsible for 33.33%. These findings are supported by Shah & Archana, (2021) who carried out a study on the removal of cadmium and cobalt in a liquid medium, they observed that bacterial strains obtained from the subsurface had the capacity to remove chromium and cadmium to varying degrees. An experiment using a packed bed column showed that bacterial strains isolated from the subsurface could potentially remove chromium from sediments with varying particle sizes. Ni and Fe were degraded moderately with *Streptomyces spp*. accounting for 16.67% and 16.03% respectively and *Bacillus spp*. accounting for 29.17 % and 26.69% respectively (Figure 3). A study by Shah et al. (2024) found out that the *Streptomyces spp*. bioactive substances have substantial antioxidant and iron-chelating properties, that can increase cell survival in harsh environments. Chromium was the least degraded with Streptomyces responsible for 6.49% while Bacillus spp. responsible for 10.38 % of degradation. A Tukey HSD post hoc test was done to confirm the significant differences between treatments. *Streptomyces spp*. exhibited significantly greater removal efficiency than *Bacillus spp*. for Zn and Cu ($p < 0.05$). On the other hand, *Bacillus spp*. demonstrated significantly higher removal of Ni, Fe, and Cr compared to *Streptomyces spp*. ($p < 0.05$). There were no statistically significant differences observed between the treatments for Cd and Co ($p > 0.05$). Murari et al. (2024) reported that *Streptomyces spp*. and *Arthrobacter crystallopoietes* were effective in bioremediation Cr (VI) in contaminated soil, with *A. crystallopoietes* achieving the highest degradation efficiency, supporting findings by Gomathy et al. (2022).

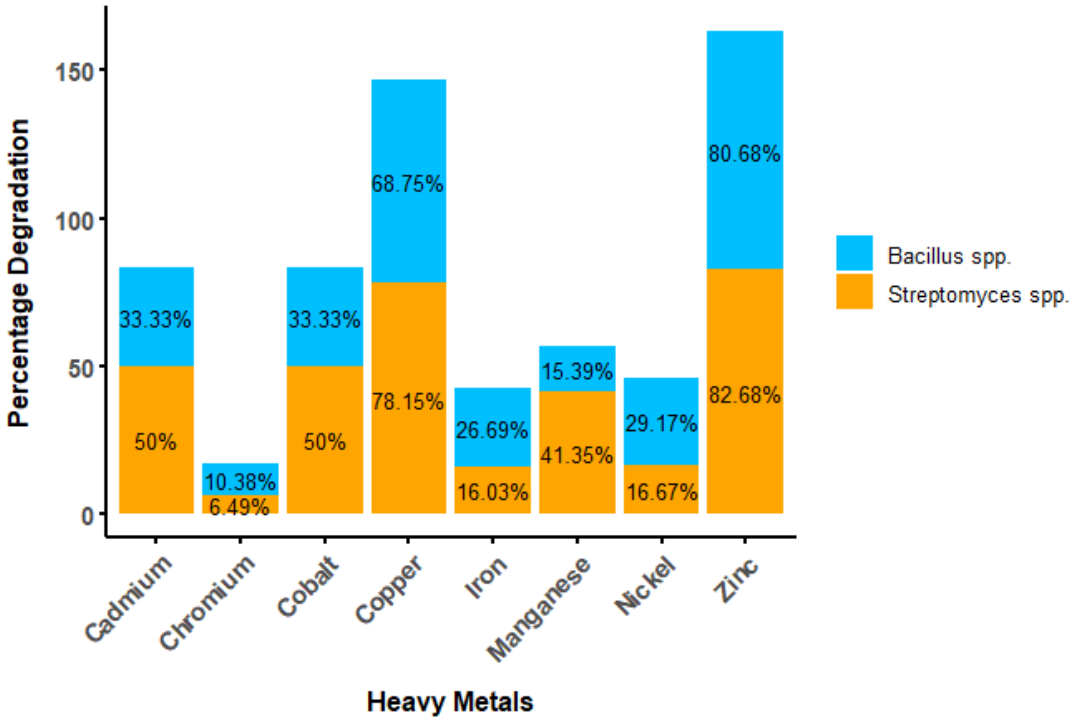

Figure 3: Percentage degradation of heavy metal elements attributed to either Streptomyces spp. or Bacillus spp.

Conclusion

Based on the results, heavy metal concentrations in soil samples from the Kipkenyo dumpsite varied among elements. Cobalt, copper, iron, nickel, and zinc were within safe limits, whereas manganese, cadmium, and chromium exceeded the permissible limits according to WHO guidelines.

The detection of fecal indicator organisms and pathogenic bacteria suggests a potential risk of disease transmission to nearby communities, underscoring the need for improved waste management and sanitation practices in Uasin Gishu county.

The Kipkenyo dumpsite microbial community comprises two functional groups: the remediation associated bacteria such as *Bacillus spp* and *Arthrobacter spp*, which indicate natural potential for heavy metal degradation, and fecal indicator and pathogenic bacteria such as *Escherichia coli, Staphylococcus*, and *Streptococcus*, which reflect environmental contamination and public health risks. These findings demonstrate that the dumpsite is both a source of pollution and a reservoir of bioremediation capable microbes, highlighting the need for improved waste management and the potential application of native bacteria in cost-effective remediation strategies for Eldoret, Uasin Gishu County.

Recommendation

The Uasin Gishu county, Department of Environment should initiate pilot-scale bioremediation projects using *Streptomyces* inoculants at the Kipkenyo site.

Further research utilizing 16S rRNA sequencing is necessary to identify the specific *Streptomyces* strains used in this study to facilitate commercial scale bio-fertilizer or inoculant production.

References

Abd Elnabi, M. K., Elkaliny, N. E., Elyazied, M. M., Azab, S. H., Elkhalifa, S. A., Elmasry, S., Mouhamed, M. S., Shalamesh, E. M., Alhorieny, N. A., Abd Elaty, A. E., Elgendy, I. M., Etman, A. E., Saad, K. E., Tsigkou, K., Ali, S. S., Kornaros, M., & Mahmoud, Y. A.-G. (2023). Toxicity of Heavy Metals and Recent Advances in Their Removal: A Review. *Toxics*, *11*(7), Article 7. https://doi.org/10.3390/toxics11070580

Abo-Alkasem, M. I., Hassan, N. H., & Abo Elsoud, M. M. (2023). Microbial bioremediation as a tool for the removal of heavy metals. *Bulletin of the National Research Centre*, *47*(1), 31. https://doi.org/10.1186/s42269-023-01006-z

Addy, R., Kalamdhad, A., & Goud, V. V. (2023). Chapter Fourteen—Insight on the prevalence of pathogens present in the municipal solid waste of sanitary landfills, dumpsites, and leachate. In K. Huang, S. Ahmad Bhat, & G. Cui (Eds.), *Fate of Biological Contaminants During Recycling of Organic Wastes* (pp. 279–295). Elsevier. https://doi.org/10.1016/B978-0-323-95998-8.00006-6

Adekanmbi, A. O., Rabiu, A. G., Ajose, D. J., Akinlabi, O. C., Bolarinwa, K. A., Farinu, E. P., Olaposi, A. V., & Adeyemi, A. O. (2024). Solid waste dumpsite leachate and contiguous surface water contain multidrug-resistant ESBL-producing Escherichia coli carrying Extended Spectrum β-Lactamase (ESBL) genes. *BMC Microbiology*, *24*(1), 308. https://doi.org/10.1186/s12866-024-03444-9

Agbeshie, A. A., Adjei, R., Anokye, J., & Banunle, A. (2020). Municipal waste dumpsite: Impact on soil properties and heavy metal concentrations, Sunyani, Ghana. *Scientific African*, *8*, e00390. https://doi.org/10.1016/j.sciaf.2020.e00390

Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., & Wang, M.-Q. (2021). Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications. *Toxics*, *9*(3), Article 3. https://doi.org/10.3390/toxics9030042

Ameen, N., Amjad, M., Murtaza, B., Abbas, G., Shahid, M., Imran, M., Naeem, M. A., & Niazi, N. K. (2019). Biogeochemical behavior of nickel under different abiotic stresses: Toxicity and detoxification mechanisms in plants. *Environmental Science and Pollution Research*, *26*(11), 10496–10514. https://doi.org/10.1007/s11356-019-04540-4

Angon, P. B., Islam, M. S., Kc, S., Das, A., Anjum, N., Poudel, A., & Suchi, S. A. (2024). Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. *Heliyon*, *10*(7). https://doi.org/10.1016/j.heliyon.2024.e28357

Behera, S., & Das, S. (2023). Potential and prospects of Actinobacteria in the bioremediation of environmental pollutants: Cellular mechanisms and genetic regulations. *Microbiological Research*, *273*, 127399. https://doi.org/10.1016/j.micres.2023.127399

Beth, C. M., & Jamal, B. K. (2023). Impacts of covid-19 measures on supply and distribution of milk on small-scale processors in Nakuru, Uasin Gishu, and Nyandarua Counties, Kenya. *African Journal of Food Science*, *17*(9), 179–191. https://doi.org/10.5897/ajfs2023.2251

Böke Özkoç, H., Aliustaoğlu, M. T., & Şentürk, İ. (2023). Bioremediation of Copper with Endophytic Bacteria *Bacillus sp.* and *Streptomyces griseus*. *Journal of Environmental Engineering*, *149*(11), 04023073. https://doi.org/10.1061/JOEEDU.EEENG-7397

Carter, S. D. (2023). *COVID-19, Supply Chain, Climate Change, and Sustainable Development in Africa: Current Business Issues in African Countries (CBIAC) Conference, Staten Island, NY, USA, April 7-8, 2022*. Springer Nature.

Chabukdhara, M., Gupta, S. K., & Nema, A. K. (2021). Heavy Metal Accumulation in Crops: Status, Sources, Risks, and Management Strategies. In *Field Practices for Wastewater Use in Agriculture*. Apple Academic Press.

Cherogony, J. (2018). *Factors Influencing Implementation Of Public -Private Partnerships In Waste Management: A Case Of Uasin Gishu County, Kenya* [Thesis, University of Nairobi]. http://erepository.uonbi.ac.ke/handle/11295/106361

Choudhary, M., Kumar, R., Datta, A., Nehra, V., & Garg, N. (2017). Bioremediation of Heavy Metals by Microbes. In S. Arora, A. K. Singh, & Y. P. Singh (Eds.), *Bioremediation of Salt Affected Soils: An Indian Perspective* (pp. 233–255). Springer International Publishing.

https://doi.org/10.1007/978-3-319-48257-6_12

Daripa, A., Malav, L. C., Yadav, D. K., & Chattaraj, S. (2023). Chapter 7—Metal contamination in water resources due to various anthropogenic activities. In S. K. Shukla, S. Kumar, S. Madhav, & P. K. Mishra (Eds.), *Metals in Water* (pp. 111–127). Elsevier. https://doi.org/10.1016/B978-0-323-95919-3.00022-7

Dey, S., Tripathy, B., Kumar, M. S., & Das, A. P. (2023). Ecotoxicological consequences of manganese mining pollutants and their biological remediation. *Environmental Chemistry and Ecotoxicology*, *5*, 55–61. https://doi.org/10.1016/j.enceco.2023.01.001

Díaz, B., Sommer-Márquez, A., Ordoñez, P. E., Bastardo-González, E., Ricaurte, M., & Navas-Cárdenas, C. (2024). Synthesis Methods, Properties, and Modifications of Biochar-Based Materials for Wastewater Treatment: A Review. *Resources*, *13*(1), Article 1. https://doi.org/10.3390/resources13010008

Enviromental Management and coordination Act 1999(Amended 2015),Waste Management regulation,2006

Fakhar, A., Gul, B., Gurmani, A. R., Khan, S. M., Ali, S., Sultan, T., Chaudhary, H. J., Rafique, M., & Rizwan, M. (2022). Heavy metal remediation and resistance mechanism of Aeromonas, Bacillus, and Pseudomonas: A review. *Critical Reviews in Environmental Science and Technology*, *52*(11), 1868–1914. https://doi.org/10.1080/10643389.2020.1863112

Fauziah, S. H., Agamuthu, P., Hashim, R., Izyani, A. K., & Emenike, C. U. (2017). Assessing the bioaugmentation potentials of individual isolates from landfill on metal-polluted soil. *Environmental Earth Sciences*, *76*(11), 401. https://doi.org/10.1007/s12665-017-6739-x

Gohad, G., & Bhendarkar, A. Y. (2025). Review Article: Hospital Acquired Infections in Immunocompromised Patients. In *Case Studies on Holistic Medical Interventions*. CRC Press.

Gunjyal, N., Rani, S., Asgari Lajayer, B., Senapathi, V., & Astatkie, T. (2023). A review of the effects of environmental hazards on humans, their remediation for sustainable development, and risk assessment. *Environmental Monitoring and Assessment*, *195*(6), 795. https://doi.org/10.1007/s10661-023-11353-z

Harish, V., Aslam, S., Chouhan, S., Pratap, Y., & Lalotra, S. (2023). Iron toxicity in plants: A Review. *International Journal of Environment and Climate Change*, *13*(8), 1894–1900. https://doi.org/10.9734/ijecc/2023/v13i82145

Harun, F. A., Yusuf, M. R., Usman, S., Shehu, D., Babagana, K., Sufyanu, A. J., Jibril, M. M., Bello, A. M., Musa, K. A., Jagaba, A. H., Shukor, M. Y., & Yakasai, H. M. (2023). Bioremediation of lead contaminated environment by *Bacillus cereus* strain BUK_BCH_BTE2: Isolation and characterization of the bacterium. *Case Studies in Chemical and Environmental Engineering*, *8*, 100540. https://doi.org/10.1016/j.cscee.2023.100540

Hashim, H. S., Zayan, M. M., Mohamed, A. A., & El rahman Abulila, H. I. A. (2026). Actinomycetes in the spotlight: Biodiversity and their role in bioremediation. *World Journal of Microbiology and Biotechnology*, *42*(2), 44. https://doi.org/10.1007/s11274-025-04610-5

Hassan, M. U., Chattha, M. U., Khan, I., Chattha, M. B., Aamer, M., Nawaz, M., Ali, A., Khan, M. A. U., & Khan, T. A. (2019). Nickel toxicity in plants: Reasons, toxic effects, tolerance mechanisms, and remediation possibilities—a review. *Environmental Science and Pollution Research*, *26*(13), 12673–12688. https://doi.org/10.1007/s11356-019-04892-x

Hembrom, S., Singh, B., Gupta, S. K., & Nema, A. K. (2020). A Comprehensive Evaluation of Heavy Metal Contamination in Foodstuff and Associated Human Health Risk: A Global Perspective. In P. Singh, R. P. Singh, & V. Srivastava (Eds.), *Contemporary Environmental Issues and Challenges in Era of Climate Change* (pp. 33–63). Springer. https://doi.org/10.1007/978-981-32-9595-7_2

Holt, J. G. (1994). *Bergey's Manual of Determinative Bacteriology*. Lippincott Williams & Wilkins.

Jain, A., Jain, R., & Jain, S. (2020). Sub-culturing of Bacteria, Fungi and Actinomycetes. In A. Jain, R. Jain, & S. Jain (Eds.), *Basic Techniques in Biochemistry, Microbiology and Molecular Biology: Principles and Techniques* (pp. 101–103). Springer US.

https://doi.org/10.1007/978-1-4939-9861-6_29

Jantschke, A. (2022). Non-silicate Minerals (Carbonates, Oxides, Phosphates, Sulfur-Containing, Oxalates, and Other Organic Crystals) Induced by Microorganisms. In A. Berenjian & M. Seifan (Eds.), *Mineral Formation by Microorganisms: Concepts and Applications* (pp. 161–241). Springer International Publishing. https://doi.org/10.1007/978-3-030-80807-5_6

Javanbakht, V., Alavi, S. A., & Zilouei, H. (2013). Mechanisms of heavy metal removal using microorganisms as biosorbent. *Water Science and Technology*, *69*(9), 1775–1787. https://doi.org/10.2166/wst.2013.718

Jepkoech, J. (2013). *Selected Heavy Metals In Water And Sediments And Their Bioconcentrations In Plant (Polygonum pulchrum) In Sosiani River, Uasin Gishu County, Kenya* [Thesis, University of Eldoret]. http://41.89.164.27:8080/xmlui/handle/123456789/880

Karadžić, I. M., Rikalović, M. G., Izrael-Živković, L. T., & Medić, A. B. (2021). Extremophilic Isolates of Pseudomonas aeruginosa as Biomarkers of Presence of Heavy Metals and Organic Pollution and Their Potential for Application in Contemporary Ecotoxicology. In *Extreme Environments*. CRC Press.

Kumar, M., Gogoi, A., Kumari, D., Borah, R., Das, P., Mazumder, P., & Tyagi, V. K. (2017). Review of Perspective, Problems, Challenges, and Future Scenario of Metal Contamination in the Urban Environment. *Journal of Hazardous, Toxic, and Radioactive Waste*, *21*(4), 04017007. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000351

Kumari, S., Agrawal, N. K., Agarwal, A., Kumar, A., Malik, N., Goyal, D., Rajput, V. D., Minkina, T., Sharma, P., & Garg, M. C. (2023). A Prominent Streptomyces sp. Biomass-Based Biosorption of Zinc (II) and Lead (II) from Aqueous Solutions: Isotherm and Kinetic. *Separations*, *10*(7), Article 7. https://doi.org/10.3390/separations10070393

Liyanage, G. Y., Wijerathna, P. A. K. C., Bandara, S. M. T. V., & Manage, P. M. (2024). Assessment of Virulence Potential and Antibiotic Resistance Profiles in E. coli Isolates from Selected Ground Water Samples Around the Control Open Dump Sites in Sri Lanka. *Waste and Biomass Valorization*, *15*(9), 5475–5485. https://doi.org/10.1007/s12649-024-02544-x

Mai, X., Tang, J., Tang, J., Zhu, X., Yang, Z., Liu, X., Zhuang, X., Feng, G., & Tang, L. (2025). Research progress on the environmental risk assessment and remediation technologies of heavy metal pollution in agricultural soil. *Journal of Environmental Sciences*, *149*, 1–20. https://doi.org/10.1016/j.jes.2024.01.045

Medfu Tarekegn, M., Zewdu Salilih, F., & Ishetu, A. I. (2020). Microbes used as a tool for bioremediation of heavy metal from the environment. *Cogent Food & Agriculture*, *6*(1), 1783174. https://doi.org/10.1080/23311932.2020.1783174

Monteiro, A., Cardoso, J., Guerra, N., Ribeiro, E., Viegas, C., Cabo Verde, S., & Sousa-Uva, A. (2022). Exposure and Health Effects of Bacteria in Healthcare Units: An Overview. *Applied Sciences*, *12*(4), Article 4. https://doi.org/10.3390/app12041958

Murgor, D. K. (2021). Changing Weather Patterns in Maize and Wheat Production against the Backdrop of Improved Access to Weather and Climate Information by Farmers in Uasin Gishu County, Kenya. *Africa Environmental Review Journal*, *4*(2), Article 2. https://doi.org/10.2200/aerj.v4i2.182

Naitore, M. E. (2018). *Numerical Modeling Of Heavy Metals In Riverine Systems In Eldoret, Uasin Gishu County, Kenya* (Doctoral dissertation, Kenyatta University).

Najim, A. A., Radeef, A. Y., al-Doori, I., & Jabbar, Z. H. (2024). Immobilization: The promising technique to protect and increase the efficiency of microorganisms to remove contaminants. *Journal of Chemical Technology & Biotechnology*, *99*(8), 1707–1733. https://doi.org/10.1002/jctb.7638

Nanda, M., Kumar, V., & Sharma, D. K. (2019). Multimetal tolerance mechanisms in bacteria: The resistance strategies acquired by bacteria that can be exploited to 'clean-up' heavy metal contaminants from water. *Aquatic Toxicology*, *212*, 1–10. https://doi.org/10.1016/j.aquatox.2019.04.011

Naseri, T., Pourhossein, F., Mousavi, S. M., Kaksonen, A. H., & Kuchta, K. (2022). Manganese bioleaching: An emerging approach for manganese recovery from spent

batteries. *Reviews in Environmental Science and Bio/Technology*, *21*(2), 447–468. https://doi.org/10.1007/s11157-022-09620-5

Nyongesa, G. M., Makokha, G., & Mbuthia, S. (2023). The Extent to Which Rainfall Variability has Affected Small Scale Dairy Farmers in Uasin-Gishu County, Kenya. *International Journal of Research and Innovation in Social Science*, *VII*(X), 1319–1338. https://doi.org/10.47772/ijriss.2023.701102

Okpa, A. M., Monago-Ighorodje, C. C., Baabel, K., & Ezim, O. E. (2024). Remediation of crude oil polluted soil using a combination of macerated cobs of Zea mays and Pleurotus ostreatus. *Scientia Africana*, *23*(2), Article 2. https://doi.org/10.4314/sa.v23i2.28

Okereafor, U., Makhatha, M., Mekuto, L., Uche-Okereafor, N., Sebola, T., & Mavumengwana, V. (2020). Toxic Metal Implications on Agricultural Soils, Plants, Animals, Aquatic life and Human Health. *International Journal of Environmental Research and Public Health*, *17*(7), Article 7. https://doi.org/10.3390/ijerph17072204

Onakpa, M. M., Njan, A. A., & Kalu, O. C. (2018). A Review of Heavy Metal Contamination of Food Crops in Nigeria. *Annals of Global Health*, *84*(3), 488–494. https://doi.org/10.29024/aogh.2314

Pal, A., Bhattacharjee, S., Saha, J., Sarkar, M., & Mandal, P. (2022). Bacterial survival strategies and responses under heavy metal stress: A comprehensive overview. *Critical Reviews in Microbiology*, *48*(3), 327–355. https://doi.org/10.1080/1040841X.2021.1970512

Park, J.-H., Kim, S.-J., Ahn, J. S., Lim, D.-H., & Han, Y.-S. (2018). Mobility of multiple heavy metalloids in contaminated soil under various redox conditions: Effects of iron sulfide presence and phosphate competition. *Chemosphere*, *197*, 344–352. https://doi.org/10.1016/j.chemosphere.2018.01.065

Pezzoni, M., Lemos, M., Pizarro, R. A., & Costa, C. S. (2022). UVA as environmental signal for alginate production in Pseudomonas aeruginosa: Role of this polysaccharide in the protection of planktonic cells and biofilms against lethal UVA doses. *Photochemical & Photobiological Sciences*, *21*(8), 1459–1472. https://doi.org/10.1007/s43630-022-00236-w

Presentato, A., Piacenza, E., Turner, R. J., Zannoni, D., & Cappelletti, M. (2020). Processing of Metals and Metalloids by Actinobacteria: Cell Resistance Mechanisms and Synthesis of Metal(loid)-Based Nanostructures. *Microorganisms*, *8*(12), 2027. https://doi.org/10.3390/microorganisms8122027

Roy, S., Gupta, S. K., Prakash, J., Habib, G., & Kumar, P. (2022). A global perspective of the current state of heavy metal contamination in road dust. *Environmental Science and Pollution Research*, *29*(22), 33230–33251. https://doi.org/10.1007/s11356-022-18583-7

Satarug, S., Vesey, D. A., Gobe, G. C., & Đorđević, A. B. (2022). The Validity of Benchmark Dose Limit Analysis for Estimating Permissible Accumulation of Cadmium. *International Journal of Environmental Research and Public Health*, *19*(23), Article 23. https://doi.org/10.3390/ijerph192315697

Shah, A. P., & Archana, G. (2021). Evaluation of bacterial strains isolated from Late Quaternary alluvial sediments spanning ~ 28 m in depth for heavy metal tolerance and Cr(VI) removal ability. *International Microbiology*, *24*(3), 385–398. https://doi.org/10.1007/s10123-021-00174-0

Shah, I., Uddin, Z., Hussain, M., Khalil, A. A. K., Amin, A., Hanif, F., Ali, L., Amirzada, M. I., Shah, T. A., Dawoud, T. M., Bourhia, M., Li, W.-J., & Sajjad, W. (2024). Streptomyces sp. From desert soil as a biofactory for antioxidants with radical scavenging and iron chelating potential. *BMC Microbiology*, *24*(1), 419. https://doi.org/10.1186/s12866-024-03586-w

Sharma, S., Tiwari, S., Hasan, A., Saxena, V., & Pandey, L. M. (2018). Recent advances in conventional and contemporary methods for remediation of heavy metal-contaminated soils. *3 Biotech*, *8*(4), 216. https://doi.org/10.1007/s13205-018-1237-8

Shetty, B. R., Jagadeesha, P. B., & Salmataj, S. A. (2025). Heavy metal contamination and its impact on the food chain: Exposure, bioaccumulation, and risk assessment. *CyTA - Journal of Food*, *23*(1), 2438726. https://doi.org/10.1080/19476337.2024.2438726

Sreedevi, P. R., Suresh, K., & Jiang, G. (2022). Bacterial bioremediation of heavy metals in wastewater: A review of processes and applications. *Journal of Water Process Engineering*, *48*, 102884. https://doi.org/10.1016/j.jwpe.2022.102884

Timková, I., Sedláková-Kaduková, J., & Pristaš, P. (2018). Biosorption and Bioaccumulation Abilities of Actinomycetes/Streptomycetes Isolated from Metal Contaminated Sites. *Separations*, *5*(4), 54. https://doi.org/10.3390/separations5040054

Verma, L., Ekka, A., Banjara, R. A., Ambade, B., Kumar, A., & Gautam, S. (2025). A Review on Bacterial Exopolysaccharides for Heavy Metal Remediation: Mechanisms, Challenges, and Sustainable Applications. *Water Environment Research*, *97*(10), e70184. https://doi.org/10.1002/wer.70184

Volarić, A., Svirčev, Z., Tamindžija, D., & Radnović, D. (2021). Microbial bioremediation of heavy metals. *Hemijska Industrija*, *75*(2), 103–115.

Yaradoddi, J. S., & Kontro, M. H. (2021). Actinobacteria: Basic Adaptation to Harsh Environments. In J. S. Yaradoddi, M. H. Kontro, & S. V. Ganachari (Eds.), *Actinobacteria: Ecology, Diversity, Classification and Extensive Applications* (pp. 69–88). Springer Nature. https://doi.org/10.1007/978-981-16-3353-9_5

Zaghloul, A., & Saber, M. (2019). Modern Technologies in Remediation of Heavy Metals in Soils. *International Journal of Environmental Pollution and Environmental Modelling*, *2*(1), Article 1.