Springer

The Impact of Heavy Metal Contamination in Soils on Soil Microbial Communities and Its Potential Health Risks for Humans

Olaniyi JohnPaul Popoola, Olusola David Ogundele, Emmanuel Abayomi Ladapo, and Samson Senbore

Abstract Heavy metal contamination poses significant threats to soil ecosystems, human health, and biodiversity due to its toxicity and persistence in the environment. Metal pollution, primarily from human activities is a significant contributor to soil levels. The most common metals include lead, cadmium, mercury, chromium, zinc, and nickel, each with unique health and environmental impacts. Understanding the impact of heavy metal pollution on soil microbial communities is crucial as they play a vital role in nutrient cycling, organic matter breakdown, and soil structure maintenance. Changes in microbial diversity can serve as early indicators of soil deterioration and provide insights for developing bioremediation approaches. These metals exhibit varying degrees of toxicity to soil microorganisms, affecting microbial biomass, diversity, and metabolic activities. These metals interfere with important physiological processes in soil microbes, such as enzymatic activities and nutrient cycling, posing threats to soil health and ecosystem functioning. Advancements in analytical methods and technologies have improved our ability to identify and measure traces of heavy metals in soil, facilitating the tracking and simulation of heavy metal pollution dynamics. Multidisciplinary research, and technological advancements are essential for developing efficient strategies to mitigate the negative effects of heavy metals on soil health. The interactions between metals and microbial diversity play a critical role in ecosystem health, biogeochemical cycles, and human welfare. Understanding microbial responses to metals, modifications to microbial communities, metal transformation and cycling, antagonistic and

O. J. Popoola (✉)
Department of Geological Sciences, Achievers University, Owo, Ondo State, Nigeria
e-mail: adewumiadeniyi@achievers.edu.ng

O. D. Ogundele
Department of Chemical Sciences, Achievers University, Owo, Ondo State, Nigeria

E. A. Ladapo
School of Earth, Environment and Society, Bowling Green, OH, USA

S. Senbore
Department of Geology, University of Pretoria, Pretoria, South Africa

S. A. Aransiola et al. (eds.), *Soil Microbiome in Green Technology Sustainability*,
https://doi.org/10.1007/978-3-031-71844-1_15

synergistic interactions, and disruptions to microbial processes and functions is crucial for controlling environmental pollution and maintaining ecosystem sustainability.

Keywords Contamination · Health risks · Heavy metals · Microbial communities · Soils

1 Introduction

1.1 Heavy Metal Contamination in Soils

Soil contamination by heavy metals poses a serious threat to ecosystems, human health, and biodiversity (Aransiola et al., 2024). The increase in heavy metal levels in soil is a result of anthropogenic activities such as mining, agriculture, industrial operations, and inappropriate waste disposal (Ahmed et al., 2022; Adewumi & Ogundele, 2024). Heavy metals that are commonly found in the environment include nickel, copper, zinc, arsenic, lead, cadmium, and mercury (Adewumi & Ogundele, 2024; Adewumi et al., 2022; Adewumi & Laniyan, 2020) (Fig. 1). Through the food chain, these activities can degrade the soil, which can result in decreased agricultural yields, changed nutritional content, and possible health risks (Adewumi & Lawal, 2022; Ferreira et al., 2022). Potable water sources and aquatic habitats may potentially be under jeopardy due to groundwater contamination (Sharma et al., 2023). Children are especially susceptible to the long-term neurological, developmental, respiratory, and carcinogenic effects of heavy metal exposure (Anyanwu et al., 2018; Adewumi, 2022).

1.2 Significance of Studying the Impact on Soil Microbial Communities

Heavy metal contamination significantly affects soil microbial populations due to their significance in soil structure, organic matter degradation, and nutrient cycling (Olaniran et al., 2013). Early warning indicators of soil degradation can be microorganisms that have changed in terms of variety, number, and activity (Bhaduri et al., 2022). Certain microbial species may flourish in the presence of high quantities of heavy metals, providing direction for bioremediation methods (Saeed et al., 2022). Symbiotic connections between plants and soil microbes are common and promote plant development and well-being (Sati et al., 2020). Pollution from heavy metals may disrupt these connections by influencing the availability and uptake of nutrients by plants (Mani & Kumar, 2014; Gonzalez-Henao & Ghneim-Herrera, 2021; Bhaduri et al., 2022; Yaashikaa et al., 2022). Changes in soil microbiology have been connected to potential threats to human health. There are a number of factors

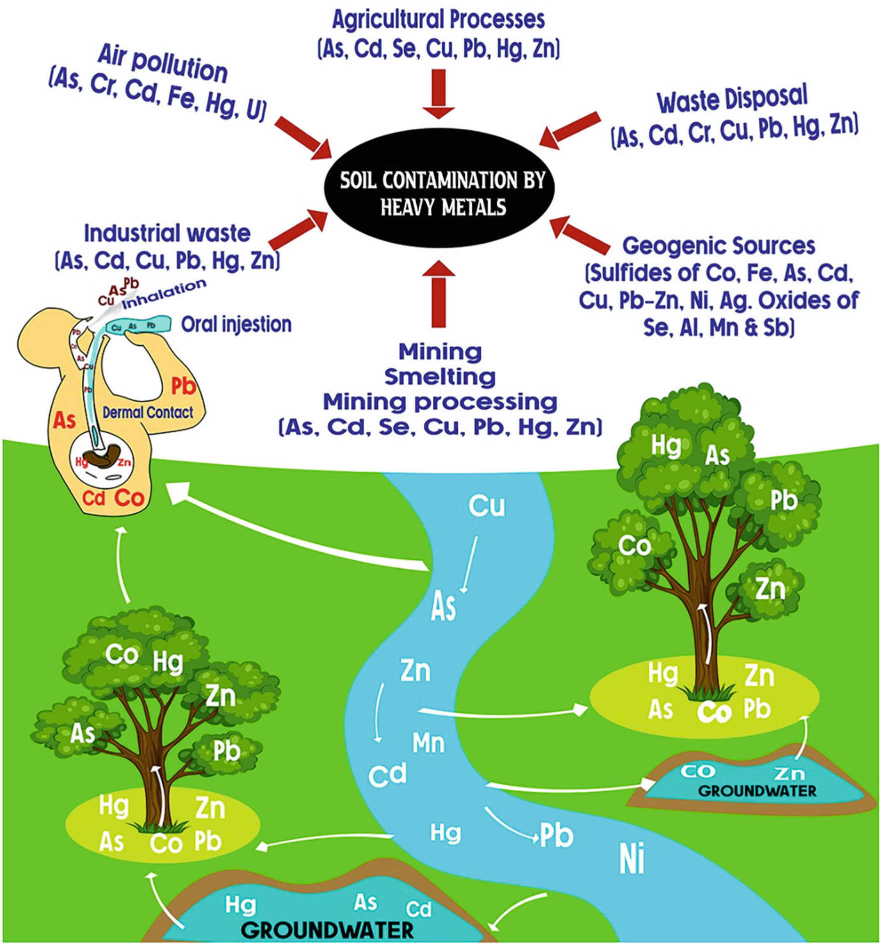

Fig. 1 Pathways of heavy metals in the environment

that can affect soil microbial populations, such as land use practices, climate change, and human activity. A decrease in the variety of microorganisms may lead to the emergence of harmful species (Hoque et al., 2021).

Urbanization and the construction of infrastructure can disturb the soil and liberate heavy metals that are held within the soil matrix (Głodowska & Wozniak, 2019; Brevik et al., 2020; Zhou et al., 2023). Leaded gasoline and lead-based paint in urban areas, inappropriate home, business, and electronic waste disposal, air deposition from industrial processes, volcanic eruptions, and wildfires are some of the past key culprits (Laniyan & Adewumi, 2019). Our understanding of the consequences of heavy metal contamination on soil ecosystems has been shaped by scientific advancements, environmental awareness, and the recognition of the ecological repercussions of human activities (Laidlaw et al., 2017; Nieder et al., 2018;

Aransiola et al., 2019). With the growing prevalence of thorough assessments of ecological issues related to heavy metal pollution in the late twentieth century, knowledge of the bioaccumulation and biomagnification of heavy metals in soil ecosystems became increasingly essential. Our ability to detect and quantify heavy metal traces in soil has improved due to technological developments in analytical techniques (Adewumi & Ogundele, 2024).

With international treaties and laws like the Minamata Convention on Mercury addressing transboundary flow and consequences on ecosystems, attitudes on heavy metal pollution have changed globally (Selin & Selin, 2020). Technological breakthroughs, multidisciplinary research, and international cooperation are necessary for the development of effective strategies to mitigate the effects of heavy metals on soil health and ecological sustainability.

2 Heavy Metals and Soil Microbial Communities

The ecosystem's health and fertility depend on the diversity of microorganisms found in soil microbial communities, which include bacteria, fungus, viruses, archaea, and protozoa (Nkongolo & Narendrula-Kotha, 2020; Punetha et al., 2022). The entire health of the ecosystem depends on the interactions between these groups and the soil environment. A number of variables, including vegetation, soil type, climate, and land management practices, have an impact on soil microbial populations. Fungi, bacteria, and archaea are the three major types of microorganisms found in soil, and they all play a role in the ecosystem (Punetha et al., 2022).

The cycling of nutrients in soil depends on microbial activity, which reduces complicated compounds into simpler ones that plants can consume (Chaves et al., 2020). The main organisms that break down dead plant matter into stable soil organic matter and release nutrients are bacteria and fungi (Gupta et al., 2022). Certain soil bacteria protect plants against illnesses by acting as their natural adversaries, maintaining plant health and productivity.

The composition and texture of the soil have an impact on microbial diversity as well; microbial communities in sandy soils differ from those in clayey soils. Microbial communities can be changed by agricultural practices like as tillage, irrigation, fertilizers, and pesticides (Wang et al., 2021a). Farmers and researchers utilize microbial markers, like diversity, microbial biomass, and enzyme activity, to assess the health of their soil (Wang et al., 2021b).

3 Heavy Metals and Their Effects on Soil Microbes

When present in excess, heavy metals—metals with large atomic weights—can have a detrimental effect on the populations of microorganisms in soil (Alengebawy et al., 2021). The causes of these metals are frequently human activities including mining,

Table 1 Effect of heavy metals on soil microbial communities

S/N	Metals	Effects on microbial communities	Reference
1.	Cadmium (Cd)	Inhibits microbial growth and enzyme activity. Reduces microbial diversity Decreases the abundance of beneficial bacteria such as Nitrosomonas and Nitrobacter, which play critical roles in nitrogen cycling Long-term exposure to cadmium could lead to the development of cadmium-resistant microbial strains, altering community composition	Giller et al. (1998) Xu et al. (2021)
2.	Lead (Pb)	Reduce microbial biomass and alters community structure Impacts nitrogen cycle by causing a significant decline in the population of nitrogen-fixing bacteria, thereby impacting soil fertility and plant growth	Giller et al. (1998) Ghosh and Singh (2005) Li et al. (2020)
3.	Mercury (Hg)	Highly toxic Significantly decreases in microbial biomass and diversity Disruption of microbial metabolic pathways, particularly those involved in carbon and sulfur cycling Increase in horizontal gene transfer, contributing to the spread of mercury resistance genes among microbial populations	Barkay et al. (2003) Wang et al. (2021a, b)
4.	Arsenic (As)	Alters microbial community composition Some microbes develop resistance to this metal It increases the number of arsenic-resistant bacteria such as Acidithiobacillus and Desulfosporosinus which possess genes that enable them to metabolize arsenic, thereby altering the biogeochemical cycling of arsenic in the environment	Mukhopadhyay et al. (2002) Zhang et al. (2022b)
5.	Zinc (Zn)	Stimulate or inhibit microbial activity depending on concentration High levels of this metal reduce microbial diversity Low concentration enhances microbial activity and biomass Negatively impacted soil enzyme activities, particularly those involved in organic matter decomposition and nutrient cycling	Baath (1989) Sun et al. (2020)
6.	Copper (Cu)	Inhibits microbial growth and enzyme activity Affects soil microbial community structure	Chen et al. (2019)

manufacturing, and farming. The diversity, quantity, and overall activity of soil microorganisms are impacted by the varying levels of toxicity of various metals (Bai et al., 2021).

The effect of heavy metals on soil microbial communities are stated out in Table 1. It is well known that lead (Pb) inhibits the development and metabolic activity of fungus and bacteria in soil, which lowers microbial diversity and biomass (Abdu et al., 2017; Liu et al., 2023). For soil microorganisms, especially bacteria, cadmium (Cd) is extremely hazardous. It damages microbial cell membranes, stifles enzyme activity, and impairs microbial respiration (Raza et al., 2020; Yang et al., 2024). Microorganisms and plants both require zinc (Zn), but excessive concentrations can be hazardous (Jagaba et al., 2022). The growth of bacteria, fungi, and archaea in the soil is impacted by copper (Cu) toxicity, which also affects the activity of the enzymes involved in nitrification and denitrification and disrupts the nitrogen cycle (Shabbir et al., 2020; Guo et al., 2021). For soil microorganisms, chromium (Cr) is toxic, causing microbial cell disruption and inhibition of metabolic processes (Monib et al., 2024). Certain soil fungi and bacteria are prevented from growing by nickel toxicity, which also alters the composition and reduces the variety of microbial communities (Zhang et al., 2022a). High levels of mercury toxicity have a substantial effect on the growth and activity of soil microorganisms, which may cause biomagnification and interfere with the nitrogen cycle in the soil (Wang et al., 2020).

4 Interactions Between Heavy Metals and Microbial Diversity

Lead, mercury, cadmium, and arsenic are examples of heavy metals that can have a substantial negative influence on human wellbeing, biogeochemical cycles, and ecosystem health. Human activities including mining, manufacturing, and farming can introduce these components. It is essential to comprehend how these metals impact microbial populations in order to manage pollution and preserve the sustainability of ecosystems (Rizvi et al., 2020; Pal et al., 2022).

Different bacteria react differently to heavy metals; some develop defense mechanisms against high metal concentrations (Verma & Kuila, 2019; Tuomainen & Candolin, 2011). Certain microorganisms may grow more slowly or be inhibited by heavy metals, whereas other germs may be stimulated or inhibited (Roane et al., 2015; Li et al., 2021). Additionally, the presence of heavy metals affects the species diversity of microbial communities, which in turn affects the flow of pollutants from soil and sediments into water bodies (Muhammad et al., 2020).

5 Bioavailability of Heavy Metals in Soils

In toxicological and environmental research, the bioavailability of heavy metals in soils is vital. It speaks of the quantity of metals that plants, microbes, and other living things are capable of absorbing (Alengebawy et al., 2021; Kumar et al., 2021). The pH of the soil, the amount of organic matter there is, the mineral content and texture of the soil, the redox conditions, microbial activity, competition and interaction, plant uptake, and the hazards to human health and the environment all have an impact on the bioavailability of heavy metals.

Since soil pH has an impact on metal speciation and plant absorption, it is a major factor influencing the bioavailability of heavy metals (Kim et al., 2015). Soil organic matter contributes to metal complexation, which can increase or decrease a metal's bioavailability (Pontoni et al., 2022). The adsorption and desorption of heavy metals are also influenced by the texture of the soil; metals are bound by clay minerals and soil particles, which lowers their bioavailability (Li et al., 2022; Lin et al., 2021; Aransiola et al., 2023). The solubility and speciation of heavy metals are influenced by redox circumstances; iron and manganese become more bioavailable in reducing settings, while less bioavailable metal forms precipitate in oxidizing ones (Caporale & Violante, 2016; Abdu et al., 2017; Pardue & Patrick, 2018).

6 Cellular and Physiological Responses of Soil Microbes to Heavy Metals

Heavy metals are enduring environmental pollutants that build up in soils as a result of manmade or natural processes (Adewumi & Ogundele, 2024). Examples of these pollutants include zinc, lead, mercury, and cadmium. Since soil microbes are more sensitive to changes in their microenvironment, they respond dynamically to heavy metal stress (Philippot et al., 2024). This includes bacteria, fungi, and archaea. It is essential to comprehend soil microbes' cellular and physiological reactions to heavy metals in order to comprehend their adaptation strategies (Loutet et al., 2021).

Microorganisms in the soil employ a variety of tactics, including mechanisms of absorption and accumulation, to control their exposure to heavy metals. Metals can be absorbed and stored as precipitates with the help of membrane transporters. Heavy metals have the potential to disrupt microbial metabolism, which can have an effect on nutrition cycling, energy production, and cellular function (Philippot et al., 2024). Enzyme activities linked to respiration, nitrogen fixation, and sulfur metabolism may be hindered or altered when exposed to heavy metal stress (Sharma et al., 2022).

Genetic alterations in soil microorganisms can result in the selection of resistant populations. Comprehending the genetic foundation of metal resistance can facilitate the creation of microbially based approaches for metal detoxification and bioremediation (Gonzalez-Henao & Ghneim-Herrera, 2021). Larger ecological processes involving plant-microbe interactions, nitrogen cycle, and soil health are impacted by heavy metals on soil bacteria.

7 Disruption of Microbial Processes and Functions

A disturbance in the activities and functions of microorganisms can have profound effects on a range of scientific fields, such as ecology, environmental science, microbiology, agriculture, and medicine. Ecosystems, diverse industrial uses, and the health of living creatures all depend on these processes. Natural or man-made disturbances to these processes include pollution, habitat loss, climate change, and modifications to land use (Gonzalez-Henao & Ghneim-Herrera, 2021).

Another effect of disruptions is the loss of biodiversity since microbial diversity is essential to the stability of ecosystems. The depletion of habitat, pollution, and invasive species are the main causes of biodiversity loss (Bissett et al., 2013). Disturbances in microbial communities can also lead to disease and pathogen emergence by fostering an environment that is conducive to the emergence and spread of diseases (Baker et al., 2022).

Microbes are essential to agricultural environments because they cycle nutrients, keep the soil healthy, and interact with plants. Microbial population changes have the potential to reduce agricultural yield, hence requiring the restoration of microbial diversity and ecosystem services.

The economy and ecology may suffer if biotechnological applications—such as wastewater treatment, biofuel production, bioremediation, and pharmaceuticals—are disrupted. Understanding the factors that obstruct microbial operations and functions—such as ecosystem restoration, sustainable land management, enhanced waste management strategies, and cutting-edge technology for observing and managing microbial communities—is essential to mitigating and managing these problems.

8 Transfer of Heavy Metals from Soil to Humans

8.1 Routes of Exposure for Humans

Anthropogenic activities such as mining, industrial processes, agricultural practices, and waste disposal can result in the accumulation of heavy metals in soil, including lead, cadmium, mercury, arsenic, and chromium. Ingestion of these metals through food crops, water, or inhalation is possible. The two main routes of exposure are through bioaccumulation in contaminated food crops such as vegetables, fruits, cereals, and rice, and through water contamination, where pollutants can reach surface water sources such as lakes, rivers, and streams. Exposure to heavy metals can also result via inhaling dust and aerosol particles contaminated with heavy metals, especially in high-pollution industrial and urban environments. Direct contact with contaminated dust or soil can also lead to heavy metal exposure, especially for young infants. It is essential to comprehend these pathways in order to lessen the risks related to exposure to heavy metals. Through targeting these pathways, we can endeavor to mitigate the hazards linked to exposure to heavy metals.

8.2 Bioaccumulation and Biomagnification of Heavy Metals

Heavy metal bioaccumulation and biomagnification are ecological processes that contribute to the gradual rise in concentration of harmful compounds within living things and across food chains (Adewumi & Lawal, 2022). These processes occur when organisms absorb materials faster than they can be metabolized or eliminated, leading to the accumulation of heavy metals in biological tissues. These pollutants can be passed to higher trophic levels through the consumption of microbes, plants, and algae, which absorb the metals from the air, water, or soil. The accumulation of heavy metals in organisms, particularly in organs like the liver, kidneys, and muscles, has significant consequences on ecosystems, animals, and human health at all trophic levels (Adewumi & Laniyan, 2020).

Biomagnification occurs when predators ingest prey with accumulated concentrations of heavy metals, leading to increased concentrations in their tissues. This poses a significant challenge for apex predators like humans, as they may be exposed to high concentrations of heavy metals like lead and mercury through their consumption of tainted meat, fish, and dairy products. Long-term exposure to these metals can lead to developmental delays, neurological diseases, and reproductive difficulties.

8.3 Health Implications of Chronic Exposure to Contaminated Environments

Long-term exposure to polluted environments, including heavy metals, pesticides, industrial chemicals, and infections, poses serious health hazards worldwide (Abioye et al., 2021). These contaminants can linger in the air, water, soil, and food, causing respiratory disorders such as lung cancer, asthma, and chronic bronchitis. In metropolitan areas with poor air quality, indoor air pollution from sources like cooking stoves, tobacco smoke, vehicles, and industries exacerbate respiratory difficulties, particularly in areas with poor air quality (Maung et al., 2022). Reproductive difficulties are also a significant health concern.

Exposure to neurotoxic compounds like lead, mercury, arsenic, and pesticides can lead to neurological problems, cognitive impairment, and neurodegenerative illnesses like Alzheimer's and Parkinson's (Nabi & Tabassum, 2022). Long-term exposure to air pollution, industrial chemicals, heavy metals, and other carcinogenic contaminants increases the risk of developing cancer (Adewumi & Laniyan, 2020; Adewumi, 2022). Endocrine-disrupting chemicals (EDCs) can cause reproductive and developmental disorders, leading to low birth weight, premature birth, birth abnormalities, and decreased fertility (Ghosh et al., 2022; Margiana et al., 2023).

Cardiovascular diseases, such as heart attacks, strokes, and hypertension, are associated with air pollution, particularly fine particulate matter (PM2.5) and nitrogen dioxide (NO_2), which can promote inflammation, oxidative stress, endothelial dysfunction, and atherosclerosis, contributing to cardiovascular morbidity and mortality (de Bont et al., 2022). Chronic exposure to these pollutants can also compromise immune function, increasing susceptibility to infections and autoimmune diseases. Persistent organic pollutants (POPs), heavy metals, and microbial pathogens can disrupt immune responses, leading to chronic inflammation, allergic reactions, and autoimmune disorders like rheumatoid arthritis and lupus (Agache et al., 2024).

Mental health effects of living in contaminated environments include stress, anxiety, depression, and reduced quality of life. Environmental degradation, pollution-related health concerns, and socioeconomic disparities contribute to mental health burdens in affected communities (Legg et al., 2023). Therefore, it is crucial to be aware of the potential health risks associated with exposure to these pollutants.

9 Health Risks Associated with Altered Soil Microbial Communities

9.1 Impact of Soil Microbial Changes on Nutrient Cycling

Changes in soil microbiology have a major effect on the cycling of nutrients, which affects plant development, soil fertility, and ecosystem output. The mediating role of microorganisms such as bacteria, fungi, and archaea in the nutrient cycle is vital for processes like plant absorption, mineralization, immobilization, and decomposition. These processes are highly susceptible to changes in microbial populations, which can modify cycling dynamics and nutrient availability.Soil bacteria engage in vital processes called decomposition and organic matter breakdown, which convert organic molecules into simpler forms and liberate nutrients like carbon, nitrogen, phosphorus, and sulfur (Aransiola et al., 2013). Changes in the makeup and activity of microbes can affect the rate and efficacy of this process. The process of converting organic nutrients into inorganic forms that plants can absorb is known as "nutrient mineralization." Microbial populations have the power to change how these processes are balanced, which can affect how readily available nutrients are in the soil (Mahala et al., 2020; Čapek et al., 2021).

In order for soil microorganisms to convert atmospheric nitrogen gas (N_2) into ammonium (NH_4^+) for plant use, nitrogen fixation and cycling are also essential activities. Changes in microbial population can have an impact on the dynamics of the nitrogen cycle and the rates at which nitrogen is fixed, which can impact soil fertility and plant uptake of nitrogen (Shafreen et al., 2021).

The cycles of phosphorus and sulfur are ones in which soil microorganisms take part. Microbial enzymes help liberate phosphorus from organic compounds and change sulfur into forms that plants can absorb (Tian et al., 2021). Microbial population changes have the potential to reduce ecosystem productivity and restrict plant nutrient availability. Because plant-microbe interactions result in symbiotic partnerships that impact ecosystem dynamics, plant health, and nutrient absorption, they are essential to the functioning of ecosystems. Plant development and productivity may be impacted by the disruption of these symbiotic relationships caused by shifts in microbial populations.

10 Potential for Pathogenic Microorganisms in Contaminated Soils

Pathogenic bacteria can be found in contaminated soils and present a serious risk to human health. Numerous sources, such as inappropriate waste management, animal excrement, industrial runoff, and home wastewater, can introduce these germs into the soil (Adewumi & Ogundele, 2024). Humans can contract bacterial infections from contaminated water and food crops, as well as by direct touch, ingestion, inhalation, or exposure to Salmonella, Listeria, Clostridium, Mycobacterium, and Escherichia coli (*E. coli*).

Giardia, Toxoplasma gondii, and Cryptosporidium are examples of protozoan pathogens that can contaminate soil through animal or human waste. This can lead to contaminated water supplies and foodborne transmission through crops grown in contaminated soil. Humans can get lung infections, systemic mycoses, and skin infections from fungi such as Aspergillus, Candida, Histoplasma, and Coccidioides.

When sick people evacuate their feces, viruses that cause diseases like hepatitis and enteric viruses can remain in soil and sediments for a long time. They can enter soil by improper waste disposal methods, runoff from agriculture, or sewage discharge. Exposure to soil-borne diseases is higher in those who work in agriculture, live near polluted areas, or are young.

Skin infections, respiratory infections, gastrointestinal problems, and systemic ailments are among the health hazards linked to coming into touch with dangerous microorganisms in polluted soils. Little ones, the elderly, expectant mothers, and people with compromised immune systems are among the vulnerable demographics.

Strategies including improving sanitary standards, correctly treating sewage, putting waste management systems into place, supporting safe farming practices, and routinely testing and monitoring soil and water quality are required to reduce the risks associated with pathogenic microorganisms in polluted soils.

10.1 Human Health Effects Linked to Disrupted Soil Microbial Communities

In order to sustain soil fertility, nutrient cycling, plant growth, and ecosystem functioning, soil microbial populations are essential. Because disturbances to these communities alter the composition and diversity of soil microorganisms, they can have a substantial effect on human health. Reduced nutrition and food security, elevated exposure to soil-borne infections, intensified airborne allergens, compromised immunological regulation, contaminated soil microbial communities, and effects on mental health and general well-being are some of the major repercussions (Kumar et al., 2022).

The cycle of nutrients and their availability to plants is facilitated by soil microbes, and their absence can result in malnutrition and deficiencies in important micronutrients such as iron, zinc, and vitamin A. Reduced food yields and nutritional quality due to unhealthy soil can have major negative health implications, especially for those who are already susceptible.

In addition to raising the possibility of human exposure to soil-borne pathogens, disturbances in soil microbial communities can also raise the risk of respiratory, gastrointestinal, and skin illnesses. Changes in soil microbial populations can worsen airborne allergen release, which is influenced by the decomposition of organic matter and the cycling of nutrients.

Disturbed soil microbial populations can disrupt immune homeostasis, resulting in immunological dysregulation and heightened susceptibility to allergies, autoimmune disorders, and inflammatory illnesses. Immune-related diseases are on the rise among urbanized populations with little access to natural settings because of reduced contact to healthy soil microbes.

Because organic pollutants, pesticides, heavy metals, and other environmental toxins can influence the fate and migration of soil microbial populations, soil microbial populations can also be associated with contaminated exposure and health hazards. Variations in the microbiological activity of soil might prolong the pesticides' environmental durability, raising the possibility of human exposure to contaminated food, water, and air.

11 Case Studies and Research Findings

11.1 Overview of Key Studies Investigating Heavy Metal Effects on Soil Microbes

Understanding the impact of heavy metals on soil microbial communities is essential for assessing the ecological consequences of soil contamination and developing strategies for soil remediation and ecosystem restoration. Over the years, numerous studies have investigated the effects of heavy metals on soil microbes, focusing on their diversity, abundance, metabolic activity, and functional diversity. Here's an overview of some key studies in this field:

1. Giller et al. (1998): This groundbreaking study used a long-term field experiment to investigate the impact of heavy metal pollution on soil microbial populations. The researchers discovered that heavy metal contamination impeded important soil processes including nutrient cycling and organic matter breakdown, decreased microbial biomass and activity, and changed the organization of microbial communities.
2. Cao et al. (2008): This study used molecular methods, including DNA sequencing and microbial functional gene analysis, to examine how soil microbial communities were affected by cadmium exposure. The findings showed that the makeup of the microbial community had changed, with some bacterial species becoming more prevalent in soils polluted with cadmium. The significance of

microbial community adaptability and resistance to heavy metal stress was emphasized by the study.

3. Chen et al. (2019): In a polluted mining region, the effect of lead pollution on soil microbial diversity and enzyme activity was evaluated by researchers. When compared to uncontaminated soils, the results indicated a considerable drop in both enzyme activity and microbial diversity in lead-contaminated soils. The study emphasized how important soil microbial communities are to the health of soil ecosystems and how sensitive they are to heavy metal contamination.
4. Ma et al. (2016): The results of several investigations on the impact of heavy metals on soil microbial communities were combined and analyzed in this meta-analysis. Consistent trends were identified by the analysis across research, such as decreased microbial biomass and diversity, modifications in the makeup of microbial communities, and adjustments in soil enzyme activity in response to heavy metal pollution. Important information on the cumulative impact of heavy metals on soil microbial communities in various ecosystems and geographical areas was obtained from the meta-analysis.
5. Sun et al. (2020): This study examined the impact of several heavy metals on soil bacterial and fungal communities in polluted mine soils using high-throughput sequencing methods. According to the findings, there were noticeable changes in the diversity and composition of the microbial community in response to heavy metal stress, with certain metal-tolerant microbial taxa becoming more prevalent in polluted soils. The study emphasised how soil ecosystem resilience may be affected by microbial communities' capacity to respond to heavy metal pollution.
6. Xiao et al. (2020): In contaminated mine soils, this study examined the effects of various heavy metals on soil bacterial and fungal communities using high-throughput sequencing techniques. In response to heavy metal stress, the results demonstrated clear changes in the diversity and composition of the microbial community, with some metal-tolerant microbial taxa becoming dominant in contaminated soils. The study emphasized the relevance of microbial community adaptation to heavy metal pollution for soil ecosystem resilience.

All things considered, this significant studies provide valuable information about the impact of heavy metals on soil microbial communities and the implications for environmental health and soil ecosystem function. By elucidating the mechanisms underpinning microbial responses to heavy metal contamination, these studies contribute to the development of workable strategies for pollution control, soil remediation, and sustainable land management techniques. More research in this area is needed to comprehend the long-term repercussions of heavy metal contamination on soil microbial populations and to develop fresh approaches to lessen its detrimental effects.

11.2 Insights from Field Experiments and Long-Term Monitoring

Experiments in the field and long-term observation studies have yielded important information about how soil bacteria are affected by heavy metal pollution. According to these studies, soil microbial communities can be affected by heavy metal pollution in terms of richness and composition, which can modify the structure of the community and repress vulnerable species. Even if metal inputs are halted, these changes might endure in the long run.

According to field research, even in the face of heavy metal stress, soil microbial communities are able to maintain ecosystem services because they still have functional redundancy. The robustness of these systems can be impacted by factors such as microbial diversity, soil properties, and metal content.

The functioning of soil ecosystems can be disrupted by heavy metal contamination, which can limit soil enzyme activity involved in nutrient cycling, organic matter breakdown, and pollutant degradation. On plant growth, soil fertility, and total ecosystem production, this may have cascade effects. When assessing the effects of heavy metals on soil microorganisms, field research and long-term monitoring have shown how crucial it is to take into account environmental parameters such soil pH, moisture, organic matter content, and land use practices.

The management and repair of soil in metal-contaminated areas are affected by these findings. Determining bioindicators of soil health, developing targeted remediation techniques, and optimizing the use of microbial-based technologies for metal detoxification and bioremediation can all be aided by knowledge of how microbial populations respond to metal contamination.

Essential empirical data on the intricate interactions between heavy metals and soil microbial populations in natural ecosystems can be obtained from field research and long-term monitoring initiatives. By implementing these findings into soil management methods, policymakers, land managers, and environmental practitioners can endeavor to limit the detrimental impacts of metal pollution on soil health and encourage the regeneration of contaminated soils to support ecosystem resilience and sustainability.

11.3 Variability in Findings and Gaps in Existing Research

Experiments in the field and long-term observation studies have yielded important information about how soil bacteria are affected by heavy metal pollution. According to these studies, soil microbial communities can be affected by heavy metal pollution in terms of richness and composition, which can modify the structure of the community and repress vulnerable species.

Even if metal inputs are halted, these changes might endure in the long run.

According to field research, even in the face of heavy metal stress, soil microbial communities are able to maintain ecosystem services because they still have functional redundancy. The robustness of these systems can be impacted by factors such as microbial diversity, soil properties, and metal content.

The functioning of soil ecosystems can be disrupted by heavy metal contamination, which can limit soil enzyme activity involved in nutrient cycling, organic matter breakdown, and pollutant degradation. On plant growth, soil fertility, and total ecosystem production, this may have cascade effects. When assessing the effects of heavy metals on soil microorganisms, field research and long-term monitoring have shown how crucial it is to take into account environmental parameters such soil pH, moisture, organic matter content, and land use practices.

The management and repair of soil in metal-contaminated areas are affected by these findings. Determining bioindicators of soil health, developing targeted remediation techniques, and optimizing the use of microbial-based technologies for metal detoxification and bioremediation can all be aided by knowledge of how microbial populations respond to metal contamination.

Essential empirical data on the intricate interactions between heavy metals and soil microbial populations in natural ecosystems can be obtained from field research and long-term monitoring initiatives. By implementing these findings into soil management methods, policymakers, land managers, and environmental practitioners can endeavor to limit the detrimental impacts of metal pollution on soil health and encourage the regeneration of contaminated soils to support ecosystem resilience and sustainability.

12 Challenges and Limitations in Existing Literature

12.1 Methodological Challenges in Studying Heavy Metal Effects on Soil Microbes

Numerous methodological issues arise in the investigation of the effects of heavy metals on soil microorganisms. These include spatial variability and sampling, which can be difficult because soil microbial populations vary geographically. Heterogeneity in contaminants and bioavailability are important concerns as well because heavy metal-contaminated soil frequently demonstrates regional variation. Sampling strategies that guarantee replication and take into consideration regional heterogeneity are crucial for obtaining trustworthy data.

Assessing the effects of heavy metals on soil microorganisms requires careful consideration of experimental design and control conditions. Experiments can have different outcomes depending on how variables like metal content, exposure duration, soil properties, and microbial inoculum are controlled. Dose-response testing, appropriate controls, and confounding variables must all be taken into account when interpreting findings.

Sample preparation, data analysis, sequencing, and DNA extraction are among the obstacles posed by microbial community analysis. The accuracy and resolution of microbial community profiles can be impacted by the use of molecular techniques, such as amplicon sequencing or metagenomics. Reducing methodological biases, standardizing procedures, and interpreting data using bioinformatics tools are all necessary for reproducibility and cross-study comparability.

Comprehending the functional implications of heavy metal impacts on soil microorganisms necessitates an ecological relevance and functional assessment. Overcoming these challenges can be aided by multidisciplinary methods such as microbial activity assays, stable isotope tracking, and functional gene analysis.

To find out how long-term exposure to heavy metals affects soil microbes and ecosystem function, field research and long-term monitoring are required. On the other hand, obstacles include environmental changes, resource scarcity, and logistical problems. Through collaborative networks, ongoing monitoring initiatives, and state-of-the-art monitoring technologies, addressing these issues can improve our comprehension of heavy metal-microbe interactions in soil ecosystems.

12.2 Variability in Study Designs and Outcomes

The variability in studies investigating the effects of heavy metals on soil microorganisms is a significant challenge. This variability can be attributed to variations in metal concentrations, microbial populations, ambient conditions, and experimental designs. To ensure the accuracy of study results, strict statistical analysis and standardization of experimental procedures are necessary.

Environmental conditions, such as soil pH, texture, organic matter concentration, moisture levels, and microbial community composition, greatly influence the way microorganisms react to heavy metal pollution. Studies conducted under disparate environmental settings may provide inconsistent results due to differences in microbial community composition and metal bioavailability. Therefore, it is crucial to incorporate environmental data and accurately characterize soil features in study designs.

Metal characteristics and speciation also play a role in the impacts of heavy metals on soil microbial communities. Differences in toxicity, solubility, and chemical forms can cause varied results in different investigations. Additionally, changes in metal speciation and interactions with soil constituents can influence microbial community dynamics and microbial-metal interactions. Understanding these concepts is crucial for accurately evaluating their impact on soil microorganisms.

Microbial community dynamics are dynamic and varied, displaying intricate relationships with environmental elements and heavy metals. Variations in microbial composition, abundance, and functional diversity can impact the sensitivity and resilience of microbial communities to heavy metal pollution. Molecular methods like functional gene analysis and DNA sequencing can shed light on these dynamics.

Geographical and temporal scales, such as experimental plot size and duration, sample intervals, and geographic locations, can also contribute to variability in research findings. Multi-site comparisons and long-term monitoring studies are needed to capture temporal and geographical heterogeneity in microbial responses and uncover underlying patterns.Data interpretation and synthesis can be challenging due to variability in research results. Integrated modelling techniques, systematic reviews, and meta-analyses can help synthesize and combine available data, identify patterns, and clarify underlying causes of variability.

12.3 Areas Requiring Further Investigation and Clarification

The understanding of heavy metals' impact on soil microorganisms has significantly improved, but there are still unanswered questions that need further research. These include the interactive effects of multiple heavy metals, metal speciation and bioavailability, microbial community resilience and adaptation, long-term monitoring and field studies, ecosystem-level responses and functional implications, and integrated risk assessment and management.

The majority of studies on the impact of heavy metals on soil microorganisms have focused on specific metals, which is essential to understand how co-contamination affects microbial responses, metal bioavailability, and ecosystem functioning. Future studies should examine how different metal concentrations and environmental circumstances affect soil bacteria in terms of additive, antagonistic, and synergistic effects.

Metal speciation and bioavailability are crucial for determining the toxicological impact of heavy metals on soil microorganisms. Advanced analytical methods like isotope tracking and synchrotron-based spectroscopy can help clarify the dynamics of metal bioavailability and speciation in soil ecosystems.

Microbial community resilience and adaptation are also essential for understanding soil microbial communities' long-term viability and ecosystem functioning. Systems biology, microbial ecology, and omics methods can provide insights into the adaptation mechanisms and functional capabilities of metal-tolerant microbial species.

Long-term monitoring and field studies are needed to evaluate the cumulative impacts of heavy metals on soil microbial communities, soil health, and ecosystem resilience over time. Combining microbial ecology and ecosystem ecology can improve the relationship between microbial responses and the consequences of heavy metal pollution on ecosystems. Addressing the complex issues of heavy metal contamination and preserving soil health and ecosystem integrity requires bridging the gap between scientific research, policy-making, and community engagement.

13 Integration of Soil Microbial and Human Health Studies

13.1 Bridging the Gap Between Soil Science and Human Health Research

"Bridging the gap between soil science and human health research" aims to bridge the gap between these two fields. Soil science focuses on soil composition, structure, and function, while human health studies focus on health-related variables. Understanding the relationship between soil quality and human health is crucial. Soil's impact on the food chain, crop nutrient content, and potential health risks like herbicides and heavy metals can be improved. This approach can lead to better environmental management, agricultural practices, and soil biodiversity. By bridging the gap, a comprehensive understanding of soil, food, and health can be achieved.

13.2 Emerging Trends and Future Directions in Research

With emerging trends highlighting the intricate connection between soil ecosystems and human health, the interaction between soil microbes and human health is changing quickly. Understanding how many facets of human health are impacted by soil microbial populations requires the application of multidisciplinary approaches. By preserving soil health, the soil microbiome affects crop quality and the cycling of nutrients. To lower the risk of diseases connected to soil, researchers are also concentrating on the transmission of diseases through the soil. They are detecting pathogens and comprehending how they propagate.

Soil plays a crucial role in climate change and human health by retaining carbon and reducing greenhouse gas emissions. It serves as a carbon sink, impacting climate resilience, public health, and food security. Future research aims to explore sustainable soil management methods to improve health outcomes and climate adaptation. Advanced technologies like metagenomics and bioinformatics are being used to study soil microbial communities, providing insights into their roles and interactions.

14 Conclusion

In summary, heavy metal contamination poses significant threats to soil ecosystems, human health, and biodiversity due to its toxicity and persistence. Anthropogenic activities contribute to escalating levels of heavy metals in soil, including lead, cadmium, mercury, arsenic, chromium, copper, zinc, and nickel. Understanding the impact on soil microbial communities is vital for nutrient cycling and soil health, as heavy metals can disrupt symbiotic plant-microbe associations, affecting agricultural sustainability.

Interdisciplinary research is crucial for addressing the complex challenges of heavy metal contamination and its impacts on ecosystems and human well-being, including adverse health effects and disruptions to soil microbial communities. Areas requiring further investigation include understanding the mechanisms of heavy metal toxicity, evaluating the long-term impacts on microbial diversity and functionality, investigating the interactions between heavy metals and other environmental factors, and studying the bioavailability and mobility of heavy metals in soil matrix.

Developing efficient bioremediation strategies is also essential, as it involves creating microbial strains with improved metal tolerance and remediation capacities and investigating the possibilities of native microbial communities for metal remediation. The wider effects of heavy metal pollution on ecosystem services that soil bacteria perform are also crucial, such as evaluating the effects of alterations in microbial populations and functions on plant production, soil fertility, carbon sequestration, and clean air and water availability.

Translating research findings into practical applications is crucial for closing the knowledge gap between scientific research and real-world applications in agriculture and environmental management. Future research should focus on converting scientific discoveries into workable plans for pollution repair and sustainable soil management.

References

Abdu, N., Abdullahi, A. A., & Abdulkadir, A. (2017). Heavy metals and soil microbes. *Environmental Chemistry Letters, 15*(1), 65–84. https://doi.org/10.1007/s10311-016-0587-x

Abioye, O. P., Ijah, U. J. J., Aransiola, S. A., Auta, S. H., & Ojeba, M. I. (2021). Bioremediation of toxic pesticides in soil using microbial products. In R. Prasad, S. C. Nayak, R. N. Kharwar, & N. K. Dubey (Eds.), *Mycoremediation and environmental sustainability. Fungal biology*. Springer. https://doi.org/10.1007/978-3-030-54422-5_1

Adewumi, A. J. (2022). Heavy metals in soils and road dust in Akure City, Southwest Nigeria: Pollution, sources, and ecological and health risks. *Exposure and Health, 14*(2), 375–392. https://doi.org/10.1007/s12403-021-00456-y

Adewumi, A. J., & Laniyan, T. A. (2020). Contamination, sources and risk assessments of metals in media from Anka artisanal gold mining area, Northwest Nigeria. *Science of the Total Environment, 718*, 137235. https://doi.org/10.1016/j.scitotenv.2020.137235

Adewumi, A. J., & Lawal, A. E. (2022). Heavy metals in paddy soils and their uptake in rice plants collected along Ogbese River, Southwest Nigeria: Implications for contamination and health risk. *Ife Journal of Science, 24*(3), 569–582. https://doi.org/10.1080/27658511.2023.2293239

Adewumi, A. J., & Ogundele, O. D. (2024). Hidden hazards in urban soils: A meta-analysis review of global heavy metal contamination (2010–2022), sources and its ecological and health consequences. *Sustainable Environment, 10*(1), 2293239. https://doi.org/10.1080/27658511.2023.2293239

Adewumi, A. J., Akinleye, C., & Akinleye, R. O. (2022). Ecological and human health implication of heavy metals in soils of urban areas of Nigeria: A systematic review. *Achievers Journal of Scientific Research, 4*(1), 95–119.

Agache, I., Akdis, C., Akdis, M., Al-Hemoud, A., Annesi-Maesano, I., Balmes, J., & Nadeau, K. C. (2024). Immune-mediated disease caused by climate change-associated environmental hazards: Mitigation and adaptation. *Frontiers in Science, 2*, 1279192. https://doi.org/10.3389/fsci.2024.1279192

Ahmed, S. F., Kumar, P. S., Rozbu, M. R., Chowdhury, A. T., Nuzhat, S., Rafa, N., & Mofijur, M. (2022). Heavy metal toxicity, sources, and remediation techniques for contaminated water and soil. *Environmental Technology and Innovation, 25*, 102114. https://doi.org/10.1016/j.eti.2021.102114

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), 42. https://doi.org/10.3390/toxics9030042

Anyanwu, B. O., Ezejiofor, A. N., Igweze, Z. N., & Orisakwe, O. E. (2018). Heavy metal mixture exposure and effects in developing nations: An update. *Toxics, 6*(4), 65. https://doi.org/10.3390/toxics6040065

Aransiola, S. A., Ijah, U. J. J., & Abioye, O. P. (2013). Phytoremediation of Lead Polluted Soil by *Glycine max L. Applied and Environmental Soil Science, 2013*, Article ID 631619. https://doi.org/10.1155/2013/631619. https://www.hindawi.com/journals/aess/2013/631619/abs/

Aransiola, S. A., Ijah, U. J. J., Abioye, O. P., & Bala, J. D. (2019). Microbial-aided phytoremediation of heavy metals contaminated soil: A review. *European Journal of Biological Research, 9*(2), 104–125. http://www.journals.tmkarpinski.com/index.php/ejbr/article/view/157

Aransiola, S. A., Ijah, U. J. J., Abioye, O. P., & Bala, J. D. (2023). Vermicompost-assisted phytoremediation of toxic trace element-contaminated soil in Madaka, Nigeria using *Melissa officinalis* L and *Sida acuta*. *International Journal of Environmental Science and Technology*. https://doi.org/10.1007/s13762-022-04105-y

Aransiola, S. A., Ijah, U. J. J., Abioye, O. P., Bala, J. D., Rivadeneira-Mendoza, R. F., Luque, R., Rodríguez-Díaz, J. M., & Maddela, N. R. (2024). Micro and vermicompost assisted remediation of heavy metal contaminated soils using phytoextractors. *Case Studies in Chemical and Environmental Engineering, 9*(2024), 100755. https://doi.org/10.1016/j.cscee.2024.100755

Baath, E. (1989). Effects of heavy metals in soil on microbial processes and populations (a review). *Water, Air, and Soil Pollution, 47*, 335–379. https://doi.org/10.1007/BF00279331

Bai, X. T., Wang, J., Dong, H., Chen, J. M., & Ge, Y. (2021). Relative importance of soil properties and heavy metals/metalloids to modulate microbial community and activity at a smelting site. *Journal of Soils and Sediments, 21*, 1–12. https://doi.org/10.1007/s11368-020-02743-8

Baker, R. E., Mahmud, A. S., Miller, I. F., Rajeev, M., Rasambainarivo, F., Rice, B. L., & Metcalf, C. J. E. (2022). Infectious disease in an era of global change. *Nature Reviews Microbiology, 20*(4), 193–205. https://doi.org/10.1038/s41579-021-00639-z

Barkay, T., Miller, S. M., & Summers, A. O. (2003). Bacterial mercury resistance from atoms to ecosystems. *FEMS Microbiology Reviews, 27*(2–3), 355–384. https://doi.org/10.1016/S0168-6445(03)00046-9

Bhaduri, D., Sihi, D., Bhowmik, A., Verma, B. C., Munda, S., & Dari, B. (2022). A review on effective soil health bio-indicators for ecosystem restoration and sustainability. *Frontiers in Microbiology, 13*, 938481. https://doi.org/10.3389/fmicb.2022.938481

Bissett, A., Brown, M. V., Siciliano, S. D., & Thrall, P. H. (2013). Microbial community responses to anthropogenically induced environmental change: Towards a systems approach. *Ecology Letters, 16*, 128–139. https://doi.org/10.1111/ele.12109

Brevik, E. C., Slaughter, L., Singh, B. R., Steffan, J. J., Collier, D., Barnhart, P., & Pereira, P. (2020). Soil and human health: Current status and future needs. *Air, Soil and Water Research, 13*, 1178622120934441. https://doi.org/10.1177/117862212093444

Cao, L., Shen, G., & Lu, Y. (2008). Combined effects of heavy metal and polycyclic aromatic hydrocarbon on soil microorganism communities. *Environmental Geology, 54*, 1531–1536. https://doi.org/10.1016/j.ese.2022.100169

Čapek, P., Choma, M., Tahovská, K., Kaňa, J., Kopáček, J., & Šantrůčková, H. (2021). Coupling the resource stoichiometry and microbial biomass turnover to predict nutrient mineralization and immobilization in soil. *Geoderma, 385*, 114884. https://doi.org/10.1016/j.geoderma.2020.114884

Caporale, A. G., & Violante, A. (2016). Chemical processes affecting the mobility of heavy metals and metalloids in soil environments. *Current Pollution Reports, 2*, 15–27. https://doi.org/10.1007/s40726-015-0024-y

Chaves, P. J. L., Cepeda, J. T., Álvarez, F. J. G., & Orzáez, M. J. H. (2020). Influence of moisture, temperature and microbial activity in biomass sustainable storage. Special focus on olive biomasses. International journal of environmental science and natural. *Resources, 25*(3), 556165. https://doi.org/10.19080/IJESNR.2020.25.556165

Chen, J., Zhang, Y., & Wei, H. (2019). Effects of copper pollution on soil microbial community and enzyme activity in orchard soils. *Journal of Soils and Sediments, 19*(2), 707–716.

de Bont, J., Jaganathan, S., Dahlquist, M., Persson, Å., Stafoggia, M., & Ljungman, P. (2022). Ambient air pollution and cardiovascular diseases: An umbrella review of systematic reviews and meta-analyses. *Journal of Internal Medicine, 291*(6), 779–800. https://doi.org/10.1111/joim.13467

Ferreira, C. S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N., & Kalantari, Z. (2022). Soil degradation in the European Mediterranean region: Processes, status and consequences. *Science of the Total Environment, 805*, 150106. https://doi.org/10.1016/j.scitotenv.2021.150106

Ghosh, M., & Singh, S. P. (2005). A review on phytoremediation of heavy metals and utilization of its byproducts. *Applied Ecology and Environmental Research, 3*(1), 1–18. https://doi.org/10.15666/aeer/0301_001018

Ghosh, A., Tripathy, A., & Ghosh, D. (2022). Impact of endocrine disrupting chemicals (EDCs) on reproductive health of human. *Proceedings of the Zoological Society, 75*(1), 16–30. New Delhi: Springer India. https://doi.org/10.1007/s12595-021-00412-3

Giller, K. E., Witter, E., & Mcgrath, S. P. (1998). Toxicity of heavy metals to microorganisms and microbial processes in agricultural soils: A review. *Soil Biology and Biochemistry, 30*(10–11), 1389–1414. https://doi.org/10.1016/S0038-0717(97)00270-8

Głodowska, M., & Wozniak, M. (2019). Changes in soil microbial activity and community composition as a result of selected agricultural practices. *Agricultural Sciences, 10*(3), 330–351. https://doi.org/10.4236/as.2019.103028

Gonzalez-Henao, S., & Ghneim-Herrera, T. (2021). Heavy metals in soils and the remediation potential of bacteria associated with the plant microbiome. *Frontiers in Environmental Science, 9*, 604216. https://doi.org/10.3389/fenvs.2021.604216

Guo, H., Gu, J., Wang, X., Song, Z., Qian, X., Sun, W., & Yu, J. (2021). Negative effects of oxytetracycline and copper on nitrogen metabolism in an aerobic fermentation system: Characteristics and mechanisms. *Journal of Hazardous Materials., 403*, 123890. https://doi.org/10.1016/j.jhazmat.2020.123890

Gupta, A., Singh, U. B., Sahu, P. K., Paul, S., Kumar, A., Malviya, D., & Saxena, A. K. (2022). Linking soil microbial diversity to modern agriculture practices: A review. *International Journal of Environmental Research and Public Health, 19*(5), 3141. https://doi.org/10.3390/ijerph19053141

Hoque, M. N., Tahjib-Ul-Arif, M., Hannan, A., Sultana, N., Akhter, S., Hasanuzzaman, M., & Brestič, M. (2021). Melatonin modulates plant tolerance to heavy metal stress: Morphological responses to molecular mechanisms. *International Journal of Molecular Sciences, 22*(21), 11445. https://doi.org/10.3390/ijms222111445

Jagaba, A. H., Kutty, S. R. M., Isa, M. H., Ghaleb, A. A. S., Lawal, I. M., Usman, A. K., & Soja, U. B. (2022). Toxic effects of xenobiotic compounds on the microbial community of activated sludge. *ChemBioEng Reviews, 9*(5), 497–535. https://doi.org/10.1002/cben.202100055

Kim, R. Y., Yoon, J. K., Kim, T. S., Yang, J. E., Owens, G., & Kim, K. R. (2015). Bioavailability of heavy metals in soils: Definitions and practical implementation—A critical review. *Environmental Geochemistry and Health, 37*, 1041–1061. https://doi.org/10.1007/s10653-015-9695-y

Kumar, V., Pandita, S., Sidhu, G. P. S., Sharma, A., Khanna, K., Kaur, P., & Setia, R. (2021). Copper bioavailability, uptake, toxicity and tolerance in plants: A comprehensive review. *Chemosphere, 262*, 127810. https://doi.org/10.1016/j.chemosphere.2020.127810

Kumar, S., Bamboriya, S. D., Rani, K., Meena, R. S., Sheoran, S., Loyal, A., & Jhariya, M. K. (2022). Grain legumes: A diversified diet for sustainable livelihood, food, and nutritional security. In *Advances in legumes for sustainable intensification* (pp. 157–178). Academic.

Laidlaw, M. A., Filippelli, G. M., Brown, S., Paz-Ferreiro, J., Reichman, S. M., Netherway, P., & Mielke, H. W. (2017). Case studies and evidence-based approaches to addressing urban soil lead contamination. *Applied Geochemistry, 83*, 14–30. https://doi.org/10.1016/j.apgeochem.2017.02.015

Laniyan, T. A., & Adewumi, A. J. (2019). Health risk assessment of heavy metal pollution in groundwater around an exposed dumpsite in southwestern Nigeria. *Journal of Health and Pollution., 9*(24), 191–210. https://doi.org/10.5696/2156-9614-9.24.191210

Legg, R., Prior, J., Adams, J., & McIntyre, E. (2023). The relations between mental health and psychological wellbeing and living with environmental contamination: A systematic review and conceptual framework. *Journal of Environmental Psychology, 87*, 101994. https://doi.org/10.1016/j.jenvp.2023.101994

Li, B., He, X., & Song, Y. (2020). Effects of lead pollution on soil microbial activity and community structure. *Environmental Pollution, 256*, 113443. https://doi.org/10.1007/s42832-022-0134-6

Li, Y., Zhang, M., Xu, R., Lin, H., Sun, X., Xu, F., & Sun, W. (2021). Arsenic and antimony co-contamination influences on soil microbial community composition and functions: Relevance to arsenic resistance and carbon, nitrogen, and sulfur cycling. *Environment International, 153*, 106522. https://doi.org/10.1016/j.envint.2021.106522

Li, Q., Wang, Y., Li, Y., Li, L., Tang, M., Hu, W., & Ai, S. (2022). Speciation of heavy metals in soils and their immobilization at micro-scale interfaces among diverse soil components. *Science of the Total Environment, 825*, 153862. https://doi.org/10.1016/j.scitotenv.2022.153862

Lin, H. Y., Chuang, T. J., Yang, P. T., Guo, L. Y., & Wang, S. L. (2021). Adsorption and desorption of Thallium (I) in soils: The predominant contribution by clay minerals. *Applied Clay Science., 205*, 106063. https://doi.org/10.3390/agronomy14040718

Liu, X., Ju, Y., Mandzhieva, S., Pinskii, D., Minkina, T., Rajput, V. D., & Rensing, C. (2023). Sporadic Pb accumulation by plants: Influence of soil biogeochemistry, microbial community and physiological mechanisms. *Journal of Hazardous Materials, 444*, 130391. https://doi.org/10.1016/j.jhazmat.2022.130391

Loutet, S. A., Chan, A. C., Kobylarz, M. J., Verstraete, M. M., Pfaffen, S., Ye, B., & Murphy, M. E. (2021). The fate of intracellular metal ions in microbes. In *Trace metals and infectious diseases [Internet]*. MIT Press. 2015. Chapter 4.

Ma, Y., Oliveira, R. S., Freitas, H., & Zhang, C. (2016). Biochemical and molecular mechanisms of plant-microbe-metal interactions: Relevance for phytoremediation. *Frontiers in Plant Science, 7*, 918. https://doi.org/10.3389/fpls.2016.00918

Mahala, D. M., Maheshwari, H. S., Yadav, R. K., Prabina, B. J., Bharti, A., Reddy, K. K., & Ramesh, A. (2020). Microbial transformation of nutrients in soil: An overview. In *Rhizosphere microbes: Soil and plant functions* (pp. 175–211). https://doi.org/10.1007/978-981-15-9154-9_7

Mani, D., & Kumar, C. (2014). Biotechnological advances in bioremediation of heavy metals contaminated ecosystems: An overview with special reference to phytoremediation. *International Journal of Environmental Science and Technology, 11*, 843–872. https://doi.org/10.1007/s13762-013-0299-8

Margiana, R., Yousefi, H., Afra, A., Agustinus, A., Abdelbasset, W. K., Kuznetsova, M., & Mohammadi, M. J. (2023). The effect of toxic air pollutants on fertility men and women, fetus and birth rate. *Reviews on Environmental Health, 38*(3), 565–576. https://doi.org/10.1515/reveh-2022-0032

Maung, T. Z., Bishop, J. E., Holt, E., Turner, A. M., & Pfrang, C. (2022). Indoor air pollution and the health of vulnerable groups: A systematic review focused on particulate matter (PM), volatile organic compounds (VOCs) and their effects on children and people with pre-existing lung disease. *International Journal of Environmental Research and Public Health, 19*(14), 8752. https://doi.org/10.3390/ijerph19148752

Monib, A. W., Niazi, P., Barai, S. M., Sawicka, B., Baseer, A. Q., Nikpay, A., & Thea, B. (2024). Nitrogen cycling dynamics: Investigating volatilization and its interplay with N2 fixation. *Journal for Research in Applied Sciences and Biotechnology, 3*(1), 17–31. https://doi.org/10.55544/jrasb.3.1.4

Muhammad, M. H., Idris, A. L., Fan, X., Guo, Y., Yu, Y., Jin, X., & Huang, T. (2020). Beyond risk: Bacterial biofilms and their regulating approaches. *Frontiers in Microbiology, 11*, 928. https://doi.org/10.3389/fmicb.2020.00928

Mukhopadhyay, R., Rosen, B. P., Phung, L. T., & Silver, S. (2002). Microbial arsenic: From geocycles to genes and enzymes. *FEMS Microbiology Reviews, 26*(3), 311–325. https://doi.org/10.1111/j.1574-6976.2002.tb00617.x

Nabi, M., & Tabassum, N. (2022). Role of environmental toxicants on neurodegenerative disorders. *Frontiers in Toxicology, 4*, 837579. https://doi.org/10.3389/ftox.2022.837579

Nieder, R., Benbi, D. K., & Reichl, F. X. (2018). Soil-borne particles and their impact on environment and human health. In *Soil components and human health*. Springer. https://doi.org/10.1007/978-94-024-1222-2_3

Nkongolo, K. K., & Narendrula-Kotha, R. (2020). Advances in monitoring soil microbial community dynamic and function. *Journal of Applied Genetics, 61*(2), 249–263. https://doi.org/10.1007/s13353-020-00549-5

Olaniran, A. O., Balgobind, A., & Pillay, B. (2013). Bioavailability of heavy metals in soil: Impact on microbial biodegradation of organic compounds and possible improvement strategies. *International Journal of Molecular Sciences, 14*(5), 10197–10228. https://doi.org/10.3390/ijms140510197

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

Pardue, J. H., & Patrick, W. H. (2018). Changes in metal speciation following alteration of sediment redox status. In *Metal contaminated aquatic sediments* (pp. 169–185). Routledge.

Philippot, L., Chenu, C., Kappler, A., Rillig, M. C., & Fierer, N. (2024). The interplay between microbial communities and soil properties. *Nature Reviews Microbiology, 22*(4), 226–239. https://doi.org/10.1038/s41579-023-00980-5

Pontoni, L., La Vecchia, C., Boguta, P., Sirakov, M., D'Aniello, E., Fabbricino, M., & Locascio, A. (2022). Natural organic matter controls metal speciation and toxicity for marine organisms: A review. *Environmental Chemistry Letters, 20*(1), 797–812. https://doi.org/10.1007/s10311-021-01310-y

Punetha, A., Punetha, S., & Khan, A. (2022). Soil community composition and ecosystem processes. In *Agriculture, environment and sustainable development: Experiences and case studies* (pp. 217–236). Springer International Publishing. https://doi.org/10.1023/A:1006299100678

Raza, A., Habib, M., Kakavand, S. N., Zahid, Z., Zahra, N., Sharif, R., & Hasanuzzaman, M. (2020). Phytoremediation of cadmium: Physiological, biochemical, and molecular mechanisms. *Biology, 9*(7), 177. https://doi.org/10.3390/biology9070177

Rizvi, A., Zaidi, A., Ameen, F., Ahmed, B., AlKahtani, M. D., & Khan, M. S. (2020). Heavy metal induced stress on wheat: Phytotoxicity and microbiological management. *RSC Advances, 10*(63), 38379–38403. https://doi.org/10.1039/D0RA05610C

Roane, T. M., Pepper, I. L., & Gentry, T. J. (2015). Microorganisms and metal pollutants. In *Environmental microbiology* (3rd ed., pp. 415–439). Elsevier. https://doi.org/10.1016/B978-0-12-394626-3.00018-1

Saeed, M. U., Hussain, N., Sumrin, A., Shahbaz, A., Noor, S., Bilal, M., & Iqbal, H. M. (2022). Microbial bioremediation strategies with wastewater treatment potentialities–A review. *Science of the Total Environment, 818*, 151754. https://doi.org/10.1016/j.scitotenv.2021.151754

Sati, D., Pandey, S. C., Pande, V., Upreti, S., Gouri, V., Joshi, T., & Samant, M. (2020). Toward an enhanced understanding of plant growth promoting microbes for sustainable agriculture. In *Recent advancements in microbial diversity* (pp. 87–112). Academic. https://doi.org/10.1016/B978-0-12-821265-3.00005-0

Selin, H., & Selin, N. E. (2020). *Mercury stories: Understanding sustainability through a volatile element*. MIT Press. https://doi.org/10.7551/mitpress/11856.001.0001

Shabbir, Z., Sardar, A., Shabbir, A., Abbas, G., Shamshad, S., Khalid, S., & Shahid, M. (2020). Copper uptake, essentiality, toxicity, detoxification and risk assessment in soil-plant environment. *Chemosphere, 259*, 127436. https://doi.org/10.1016/j.chemosphere.2020.127436

Shafreen, M., Vishwakarma, K., Shrivastava, N., & Kumar, N. (2021). Physiology and distribution of nitrogen in soils. In *Soil nitrogen ecology* (pp. 3–31). Springer International Publishing. https://doi.org/10.1007/978-3-030-71206-8_1

Sharma, P., Chouhan, R., Bakshi, P., Gandhi, S. G., Kaur, R., Sharma, A., & Bhardwaj, R. (2022). Amelioration of chromium-induced oxidative stress by combined treatment of selected plant-growth-promoting rhizobacteria and earthworms via modulating the expression of genes related to reactive oxygen species metabolism in *Brassica juncea*. *Frontiers in Microbiology, 13*, 802512. https://doi.org/10.3389/fmicb.2022.802512

Sharma, A. K., Sharma, M., Sharma, A. K., & Sharma, M. (2023). Mapping the impact of environmental pollutants on human health and environment: A systematic review and meta-analysis. *Journal of Geochemical Exploration, 255*, 107325. https://doi.org/10.1016/j.gexplo.2023.107325

Sun, R., Zhang, X., & Guo, X. (2020). Influence of zinc contamination on soil microbial communities and enzyme activities in agricultural soils. *Ecotoxicology and Environmental Safety, 189*, 109966.

Tian, J., Ge, F., Zhang, D., Deng, S., & Liu, X. (2021). Roles of phosphate solubilizing microorganisms from managing soil phosphorus deficiency to mediating biogeochemical cycle. *Biology, 10*(2), 158. https://doi.org/10.3390/biology10020158

Tuomainen, U., & Candolin, U. (2011). Behavioural responses to human-induced environmental change. *Biological Reviews, 86*(3), 640–657. https://doi.org/10.1111/j.1469-185X.2010.00164.x

Verma, S., & Kuila, A. (2019). Bioremediation of heavy metals by microbial process. *Environmental Technology and Innovation, 14*, 100369. https://doi.org/10.1016/j.eti.2019.100369

Wang, L., Wang, L. A., Zhan, X., Huang, Y., Wang, J., & Wang, X. (2020). Response mechanism of microbial community to the environmental stress caused by the different mercury concentration in soils. *Ecotoxicology and Environmental Safety., 188*, 109906. https://doi.org/10.1016/j.ecoenv.2019.109906

Wang, Y., Feng, J., & Lin, Q. (2021a). Impact of mercury contamination on microbial communities and function in freshwater sediments. *Science of the Total Environment, 753*, 141826.

Wang, L., Kaur, M., Zhang, P., Li, J., & Xu, M. (2021b). Effect of different agricultural farming practices on microbial biomass and enzyme activities of celery growing field soil. *International Journal of Environmental Research and Public Health, 18*(23), 12862. https://doi.org/10.3390/ijerph182312862

Xiao, W., Ye, X., Liu, C., Cheng, X., Zhu, L., & Zhou, H. (2020). Effects of heavy metals on microbial communities in soils under different flooding conditions: A high-throughput sequencing analysis. *Journal of Environmental Management, 264*, 110454. https://doi.org/10.1016/j.jenvman.2020.110454

Xu, M., Zhang, H., & Wang, Q. (2021). Impact of cadmium pollution on soil microbial community structure and diversity in different land use patterns. *Journal of Hazardous Materials, 407*, 124382.