

Review article

Bioremediation of Heavy Metal-Contaminated Soils: A Systematic Review of Applied Technologies in the Philippines**Cyril John C. Nagal^{1,2*} and Badi R. Samaniego¹***¹School of Environmental Science and Management, University of the Philippines Los Baños, Laguna, Philippines**²College of Agriculture, University of Science and Technology of Southern Philippines, Claveria 9004, Philippines*

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Abstract

Heavy metal contamination in soils poses a severe environmental and agricultural challenge, jeopardizing ecosystem health, food safety, and public health on a global scale. In the Philippines, where industrial and mining activities intensify these risks, sustainable remediation strategies are urgently needed. Contaminants such as copper, nickel, and lead are by-products of mining and industrial activities, posing risks to public health and agriculture. This study aims to systematically review bioremediation technologies applied to these contaminants, examining their effectiveness and limitations in the Philippine context. A systematic review methodology was employed, drawing data from relevant studies screened for relevance, quality, and applicability to the country's environmental conditions, and focusing on quantitative results in contaminated soil areas, especially those impacted by mining. Key findings indicate that phytoremediation is the most commonly applied technique, with significant use of hyperaccumulator plants for copper and arsenic. Mycoremediation and microbial methods also show potential, although their effectiveness varies based on biological, environmental, and soil characteristics. Limitations such as limited bioavailability of metals and high variability in plant uptake capacity were noted, emphasizing the need for integrated, site-specific approaches. Hence, while bioremediation shows promise as a sustainable, cost-effective solution for heavy metal contamination, further research into plant-microbe combinations and natural chelants is essential for optimizing remediation in diverse soil and environmental contexts in the Philippines.

Keywords: bioremediation; heavy metal contamination; soil health; phytoremediation; mycoremediation; microbial remediation

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1. Introduction

Healthy soils are the foundation of environmental sustainability, agricultural productivity, and societal well-being. Soils provide essential ecosystem services, including nutrient cycling, water filtration, carbon sequestration, and support for plant growth, which are crucial for maintaining biodiversity and food security (Panagos et al., 2022). In agriculture, soil fertility directly impacts crop yields, food quality, and resilience to climate change (Qiao et al., 2022). Soil health is therefore vital to achieving global goals, such as those outlined in the United Nations' Sustainable Development Goals (SDGs), which emphasize the importance of sustainable agricultural practices to ensure food security and improved nutrition (Bouma et al., 2021). The degradation of soil ecosystems threatens these services, undermining environmental health and agricultural systems that society depends on.

One of the most pressing threats to soil health is the accumulation of heavy metals, a widespread issue in industrialized and developing regions alike (Li et al., 2019). Heavy metals such as arsenic, cadmium, lead, and nickel accumulate in soils due to activities like mining, industrial waste disposal, and the excessive use of fertilizers and pesticides. These metals are toxic and non-degradable, remaining in the environment for long periods and posing serious risks to human health, food safety, and ecosystems (Abdullahi et al., 2021). The contamination of agricultural soils, in particular, compromises crop safety, leading to the bioaccumulation of toxic metals in the food chain, which can result in chronic health issues such as cancer, neurological disorders, and organ damage (Rashid et al., 2023). Furthermore, the contamination impairs soil biological functions, reduces crop yields, and threatens biodiversity (Munir et al., 2021).

Bioremediation has emerged as a promising solution for mitigating heavy metal contamination in soils. This process uses plants, fungi, bacteria, and other microorganisms to immobilize, transform, or extract heavy metals from contaminated soils (Saha et al., 2021). Bioremediation is gaining attention due to its sustainability, cost-effectiveness, and ability to restore soil health without causing further environmental harm, unlike traditional remediation methods that often involve chemicals or excavation (Ashraf et al., 2019). The potential for in-situ treatment, combined with reduced energy consumption and lower costs, makes bioremediation a suitable approach for regions with limited resources (Sims et al., 2019). However, the effectiveness of bioremediation can vary depending on factors such as soil properties, metal bioavailability, and the biological traits of the species used for remediation (Alori et al., 2022).

International research has increasingly recognized the global threat of soil contamination by heavy metals and has focused on the application of bioremediation technologies (Emenike et al., 2018). Studies conducted in countries like China, India, and the United States have shown the effectiveness of phytoremediation using hyperaccumulator plants and microbial-assisted techniques in removing heavy metals from soils (Zhang et al., 2024). In addition, the development of chelant-enhanced bioremediation has expanded the capacity to mobilize and extract heavy metals that are otherwise immobile in soils (Marques et al., 2009). Despite these advancements, international studies have highlighted challenges such as species variability, limited scalability, and the need for further research on optimizing bioremediation in diverse environmental conditions (Mani & Kumar, 2013).

In Southeast Asia, where agricultural productivity and environmental health are critical to the region's economy and food security, studies on bioremediation have begun to address the widespread contamination of soils by heavy metals. Research in countries like Vietnam, Indonesia, and Thailand has demonstrated the potential of local plant species

(Ariyakanon, 2023). However, many of these studies are at a nascent stage, with limited long-term field trials or large-scale applications. The diversity of ecosystems and soil conditions in Southeast Asia also requires more localized studies to determine the effectiveness of various bioremediation techniques (Oladoye et al., 2022).

In the Philippines, heavy metal contamination is particularly prevalent in areas affected by mining activities, industrial waste discharge, and improper agricultural practices. A clearer understanding of local soil conditions is essential for contextualizing the challenges and prospects of bioremediation. Philippine soils are derived from diverse parent materials such as volcanic tuff, sedimentary rocks, and ultramafic bedrock, contributing to the development of various soil orders including Andisols, Vertisols, and Acrisols. These soils are extensively utilized for agriculture, forestry, and mineral extraction, making them highly susceptible to anthropogenic contamination. Common pollutants, particularly heavy metals like copper, lead, arsenic, and nickel, have been reported in areas such as Surigao del Norte, Zambales, and Marinduque (Trocio & Paguntalan, 2023). While initial studies have explored the potential of hyperaccumulator plants and microorganisms for bioremediation, current research remains fragmented and largely limited to pilot-scale experiments. Moreover, the interactions between native plant species, local soil characteristics, and indigenous microbial communities are not yet fully elucidated, underscoring a significant research gap in the localized application and scalability of bioremediation technologies.

Despite these research efforts, there is still a considerable gap in understanding the efficacy of bioremediation across different environmental contexts, particularly in tropical climates like those in the Philippines. While laboratory studies have shown promise, field applications remain limited, and questions regarding the scalability, economic feasibility, and long-term sustainability of bioremediation projects persist. This study aims to address these gaps by conducting a systematic review of bioremediation technologies applied to heavy metal-contaminated soils in the Philippines. By analyzing the current state of bioremediation in the country, this paper seeks to provide actionable insights that can guide future remediation efforts and inform policies to address soil contamination at a national level.

Driven by the urgent need to rehabilitate contaminated soils in the Philippines, where mining, industrial activities, and agriculture continue to pose environmental challenges, this study will explore applications of bioremediation in the country. Given the increasing pressure on agricultural land and the risks to public health, it is critical to explore sustainable, low-cost remediation techniques that can be applied in diverse environmental conditions. Hence, this paper will not only contribute to the scientific understanding of bioremediation but will also offer practical recommendations for policymakers, landowners, and communities to address heavy metal contamination, ensuring the restoration of healthy soils and the sustainability of agricultural practices in the Philippines.

2. Methods

The methodology for this systematic review was adapted from Siri et al. (2023), who studied antimicrobial resistance in Southeast Asian water environments. Modifications were made to certain steps to tailor the approach to the objectives and requirements of this study on bioremediation of heavy metal-contaminated soils.

2.1 Search strategy

A targeted search strategy was developed using specific terms related to bioremediation in the Philippines within the context of soil and land contamination by heavy metals. The terms included keywords such as "heavy metals-contaminated soils" and "bioremediation." Three major databases—Web of Science, Scopus, and ScienceDirect—were utilized to identify relevant peer-reviewed articles. These databases were selected for their comprehensive coverage of scientific literature and their inclusion of internationally recognized data sources, particularly in the fields of bioremediation and heavy metal accumulation (AIRyalat et al., 2019).

Search results were systematically filtered to remove duplicate entries, and articles that did not meet the inclusion criteria were excluded from further review. Only studies that were open-access and available in full text were included to ensure transparency and accessibility of the data.

2.2 Study selection and review

The primary criterion for study selection was the relevance to the geographical and environmental context of the Philippines. Only studies that applied bioremediation techniques, technologies, or complementary processes to remediate heavy metal-contaminated soils and land areas within the Philippines were considered. Furthermore, the studies had to be quantitative in nature to align with the methodological requirements of the review.

Additional criteria included the following: Inclusion - Articles written in English and focused on soil and land contamination; Exclusion - Reviews, guidelines, books, studies on water environments, and those not available in full text were excluded, as outlined in Figure 1. Each article was independently assessed by the author to determine whether it met the predefined criteria for inclusion in this review. This systematic approach ensures that the selected studies are contextually relevant, methodologically sound, and provide robust quantitative data on bioremediation practices in the Philippines.

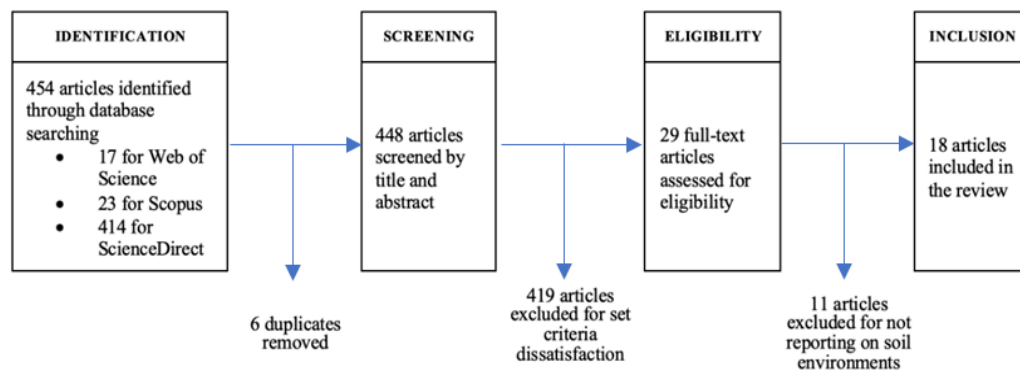


Figure 1. Search flow diagram of systematic literature review

3. Overview of Bioremediation in the Philippines

This systematic review identified 454 articles through a comprehensive search of the Web of Science, Scopus, and ScienceDirect databases. After removing six duplicates, 448 articles remained. Title and abstract screening led to the exclusion of 419 articles, resulting in 29 full-text studies for further evaluation. Following full-text review, 20 studies were retained, with two additional exclusions. Ultimately, 18 quantitative studies were deemed eligible and included in this review. The search flow diagram outlines this process (Figure 1).

The selected studies are primarily concentrated in regions impacted by mining activities, particularly Surigao del Norte and Marinduque, with additional research conducted in agricultural and forested areas in Luzon and the Visayas. This geographical focus on areas with significant soil contamination underscores the urgent need for effective bioremediation strategies across diverse environmental settings in the Philippines. The distribution of studies reflects a localized approach, taking into account the distinct ecological and socio-economic conditions of each region. This targeted approach provides valuable insights into the remediation challenges and opportunities in addressing soil degradation and heavy metal contamination in the country.

4. Bioremediation Technologies for Heavy Metal-Contaminated Soils

Table 1 summarizes 18 studies focused on the bioremediation of soils in the Philippines, showcasing various bioremediation methods, supplementary technologies, and targeted heavy metals. Phytoremediation emerged as the most frequently applied technique, used in 12 of the studies, involving processes such as phytoextraction and phytostabilization. Mycoremediation was employed in three studies, leveraging fungal species for the uptake and transformation of heavy metals, while cyanobacterial and bacterial bioremediation methods were each utilized in two studies, demonstrating the potential of microbial agents in soil remediation.

Alongside bioremediation techniques, a variety of supplementary processes were used. These technologies provided detailed analyses of metal interaction at the microscopic level. Bioaccumulation and translocation assessments were also prominent, particularly in evaluating the movement and storage of heavy metals within biological systems. The use of microbial biofertilizers, including mycorrhizal inoculants and plant growth-promoting rhizobacteria (PGPR), played a significant role in enhancing plant resilience in contaminated soils.

Heavy metals targeted in the studies were diverse, with copper (Cu) being the most common, addressed in seven studies, particularly those related to mining activities. Nickel (Ni) was another frequently targeted metal, with significant attention given to its presence in nickeliferous soils. Lead (Pb), arsenic (As), cadmium (Cd), chromium (Cr), zinc (Zn), and manganese (Mn) were also studied across different environments. These studies highlight the extensive range of bioremediation approaches being explored in the Philippines, underpinned by advanced analytical techniques and targeted toward mitigating the environmental impact of heavy metal contamination. The integration of bioremediation with supplementary technologies underscores the potential for holistic approaches to managing soil pollution in diverse ecosystems.

To provide a comprehensive understanding of the current state of bioremediation research in the Philippines, this review synthesized findings from 18 peer-reviewed publications that met the inclusion criteria. The succeeding sections of the paper (Sections 5

Table 1. General Information on the included studies on bioremediation of soils in the Philippines (n=18)

Title of the Study (Author)	Bioremediation Used	Other Technologies/Processes Used/Applied in the Study	Heavy Metal
<i>Pteris melanocaulon</i> Fée is an As hyperaccumulator (Claveria et al., 2019a)	Phytoremediation - Phytoextraction	Hydride vapor generation	Arsenic (As)
Localization of nickel in the hyperaccumulator plant <i>Breynia cernua</i> (Poir.) Mull.Arg. discovered in the nickeliferous laterites of Zambales, the Philippines (Gotera et al., 2019)	Phytoremediation - Phytoextraction	Dimethylglyoxime (DMG) Staining, Optical Microscopy	Nickel (Ni)
Copper uptake by <i>Pteris melanocaulon</i> Fée from a Copper-Gold mine in Surigao del Norte, Philippines (Benjamin et al., 2019)	Phytoremediation	Phytostabilization	Copper (Cu)
The identification of indigenous Cu and As metallophytes in the Lepanto Cu-Au Mine, Luzon, Philippines (Claveria et al., 2019b)	Phytoremediation	Absorption and Translocation	Copper (Cu), Arsenic (As)
Evaluation of Tolerance and Uptake of Cd and Mn for Microfungi <i>Aspergillus flavus</i> , <i>Aspergillus oryzae</i> , and <i>Aspergillus terreus</i> Isolated from Landfill Soil Collected from Bangar, La Union, Philippines (Arellano et al., 2024)	Mycoremediation	Soil Analysis (for Fe, Mn, Cr), Pollution Index (PI) Nemerow	Cadmium (Cd), Manganese (Mn)
Evaluating Microbial Biofertilizers for Root Colonization Potential in Narra (<i>Pterocarpus indicus</i>) (Magsayo et al., 2024)	Phytoremediation	Microbial Biofertilizers (MYKORICH®), Mycorrhizal Fungi	Iron (Fe), Nickel (Ni)
Growth Response of Narra Seedlings to Microbial Biofertilizer Applications in Mined-Out Soils (Magsayo et al., 2023)	Phytoremediation	Microbial Biofertilizers (AMF, Nitrogen-fixing bacteria)	Nickel (Ni)
Effects of Heavy Metal-Tolerant Microorganisms on the Growth of Narra Seedlings (Yuniarti et al., 2022)	Phytoremediation	Plant Growth-Promoting Rhizobacteria (PGPR), Compost Amendment	Copper (Cu)

Table 1. General Information on the included studies on bioremediation of soils in the Philippines (n=18) (continued)

Title of the Study (Author)	Bioremediation Used	Other Technologies/Processes Used/Applied in the Study	Heavy Metal
In Situ Bioremediation and Crop Growth Promotion Using Trichoderma Microbial Inoculant (TMI) (Cuevas & Banaay, 2022)	Mycoremediation	Trichoderma Microbial Inoculant (TMI), Rice Straw Compost (RSC)	Copper (Cu)
Potential Hyperaccumulator Plants for Sustainable Environment in Tropical Habitats (Castañares & Lojka, 2020)	Phytoremediation	Soil and Plant Elemental Analysis	Manganese (Mn), Magnesium (Mg), Iron (Fe)
Assessment of <i>Alternanthera sessilis</i> and <i>Aster philippinensis</i> as Excluders in Small-Scale Cu–Au Site (Sanqui et al., 2020)	Phytoremediation	Bioaccumulation/Translocation Assessment, SEM-EDX	Copper (Cu), Lead (Pb), Zinc (Zn), Arsenic (As)
Metagenomic Analysis Reveals the Presence of Heavy Metal Response Genes from Cyanobacteria Thriving in Balatoc Mines, Benguet Province, Philippines (Sanchez & Cao, 2019)	Cyanobacterial Bioremediation (<i>Leptolyngbya sp.</i>)	Shotgun Metagenomic Sequencing, Bioinformatics Tools (CLARK, Prokka)	Copper (Cu), Zinc (Zn), Lead (Pb), Cadmium (Cd)
Multimetal Resistant, Alkalitolerant Bacteria Isolated from Serpentinizing Fluid-Associated Sediments and Acid Mine Drainage in the Zambales Ophiolite, the Philippines (Vallalar et al., 2019)	Bacterial Bioremediation (<i>Bacillus sp.</i>)	Isolation and Characterization of Metal-Resistant Bacteria, TEM	Chromium (Cr), Copper (Cu), Cobalt (Co), Nickel (Ni), Zinc (Zn)
Heavy Metal Tolerance and Removal Capacity of Trichoderma species Isolated from Mine Tailings in Itogon, Benguet (Tansengco et al., 2018)	Mycoremediation (Trichoderma species) through Biosorption	Bioaccumulation, Extracellular Sequestration, Biotransformation	Chromium (Cr), Copper (Cu)
Isolation, Characterization, and Rapid Screening of Copper-Tolerant Cyanobacteria Consortia from Mining Sites and a Strawberry Farm in Benguet Province, Philippines (Sanchez et al., 2017)	Cyanobacterial Bioremediation (Cyanobacteria consortia)	Isolation of Cyanobacteria, Characterization, Growth Measurement, Statistical Analysis, Physicochemical Soil Analysis	Copper (Cu)

Table 1. General Information on the included studies on bioremediation of soils in the Philippines (n=18) (continued)

Title of the Study (Author)	Bioremediation Used	Other Technologies/Processes Used/Applied in the Study	Heavy Metal
Jatropha Curcas for Bioenergy and Bioremediation in Mine Tailing Area in Mogpog, Marinduque, Philippines (Aggangan et al., 2017)	Phytoremediation (Phytostabilization)	Compost application, mycorrhizal inoculation	Lead (Pb), Zinc (Zn), Copper (Cu)
Phytoextraction of Lead-Contaminated Soil Using Vetivergrass, Cogongrass, and Carabaograss (Paz-Alberto et al., 2007)	Phytoremediation (Phytoextraction)	N/A	Lead (Pb)
Draft Genome Sequence of the Phosphate-Solubilizing Rhizobacterium <i>Burkholderia pseudomultivorans</i> Strain MPSB1, isolated from a Copper Mined-Out Site (Aba-Regis et al., 2021)	Bacterial Bioremediation	Phosphate solubilization, heavy metal efflux pumps, siderophore production, quorum sensing	Copper (Cu), Iron (Fe) (Potential for multiple heavy metals)

and 6) present a thematic summary and critical analysis of these studies, focusing on the types of bioremediation technologies applied, their effectiveness, and the contexts in which they were implemented. This structured synthesis aims to highlight prevailing trends, identify research gaps, and evaluate the practical applicability of these technologies within the Philippine setting. By framing the discussion around the reviewed literature, the subsequent sections seek to avoid redundancy and ensure that key insights are coherently integrated into the overall narrative of this study.

5. Factors Influencing the Effectiveness of Bioremediation Technologies in Remediating Heavy Metal-Contaminated Soils

5.1 Biological characteristics of organisms

Key factors affecting bioremediation are the biological traits of hyperaccumulator plants and microorganisms employed in the process (Sanqui et al., 2020). These biological agents play a central role in the uptake, translocation, and stabilization of heavy metals in contaminated soils. For instance, plant species such as *Pteris melanocaulon* have demonstrated strong arsenic hyperaccumulation capabilities. Their effectiveness is largely attributed to specific physiological traits—such as root system architecture, shoot-to-root biomass ratio, and translocation efficiency—that determine the plant's capacity to extract and store metals in harvestable parts (Claveria et al., 2019b). These traits not only influence the uptake rate of contaminants but also affect the feasibility of repeated harvest cycles for sustained remediation.

Similarly, Gotera et al. (2019) emphasized the importance of bioaccumulation and translocation factors in assessing the suitability of a species for phytoremediation. In their study, the nickel accumulation and movement within plant tissues were quantitatively analyzed, showing that species with high translocation factors can effectively transport metals from roots to shoots—an essential trait for phytoextraction. However, these characteristics vary significantly across species, necessitating careful selection based on site-specific contaminants and soil conditions.

This variability is further exemplified in the comparative study conducted by Paz-Alberto et al. (2007), which investigated several local plant species for their phytoremediation potential in heavy metal-contaminated soils. Among the species evaluated—Talahib (*Saccharum spontaneum*), Cogon grass (*Imperata cylindrica*), and *Calypocarpus vialis*—the results showed marked differences in their uptake capacities and tolerance to cadmium, lead, and copper. *Talahib* demonstrated high tolerance and substantial metal uptake, particularly for lead, but had limited translocation efficiency, meaning the metal largely remained in the root zone. In contrast, *Calypocarpus vialis* showed better shoot translocation but was less effective in metal accumulation overall. Cogon grass, although widespread and resilient, showed only moderate remediation potential. These comparisons highlight that not all hyperaccumulator candidates are equally effective across different metals or environmental conditions.

Such differences underscore the importance of selecting plant species not only for their ability to survive in contaminated environments but also for their specific accumulation and translocation properties. Sanchez et al. (2017) further affirmed that environmental factors such as soil pH, organic matter, and metal bioavailability interact with plant physiology to influence remediation outcomes. Therefore, choosing the most appropriate species requires an integrative understanding of both plant traits and site-specific conditions.

The heterogeneity in performance among plant species points to a broader challenge in scaling phytoremediation practices in the Philippines. Many of the local studies remain limited to experimental plots or greenhouse conditions, which may not fully capture field complexities. Future research should therefore emphasize field-based trials, long-term monitoring, and comparative studies across ecological zones to better assess the real-world applicability of these species.

5.2 Soil properties

Soil properties such as pH, texture, organic matter content, and cation exchange capacity (CEC) are central to the effectiveness of bioremediation processes (Magsayo et al., 2024). These parameters govern the bioavailability of heavy metals, which in turn determines the extent to which contaminants can be absorbed by hyperaccumulator plants or remediating microorganisms. While studies like Claveria et al. (2019) have noted that variability in total arsenic concentrations across different sites affects uptake levels, it is increasingly evident that total metal content alone does not sufficiently predict metal bioavailability or phytoremediation success. This metric indicates only the potential reservoir of contaminants but does not reflect their chemical speciation or mobility in the soil matrix—two factors that are far more crucial to uptake efficiency.

Among the most critical soil properties influencing metal uptake is soil pH. Soil pH not only dictates the solubility of heavy metals and arsenic but also determines the surface charge of soil particles and the ionic forms in which contaminants exist. For example, under acidic conditions, metals like lead, cadmium, and zinc become more soluble and thus more bioavailable, increasing the likelihood of plant absorption. Conversely, in alkaline soils, metals tend to form insoluble hydroxides or carbonates, rendering them less accessible to roots (Benjamin et al., 2015). Arsenic, which primarily exists as an anion in the form of arsenate (AsO_4^{3-}) or arsenite (AsO_3^{3-}), also exhibits pH-dependent behavior. At lower pH levels, arsenate becomes more tightly bound to soil particles such as iron oxides, reducing its mobility. This pH-governed availability underscores the need to tailor bioremediation approaches to site-specific soil chemistry.

Another important factor is cation exchange capacity (CEC)—a measure of a soil's ability to retain and exchange positively charged ions. High CEC soils, typically rich in clay and organic matter, can adsorb more metal cations, such as nickel, zinc, and copper, thereby modulating their immediate bioavailability. However, while CEC enhances the retention of many cationic metals, its role in arsenic retention is less pronounced due to the anionic nature of arsenic species. This distinction highlights the complexity of soil-contaminant interactions and suggests that bioremediation strategies must consider both the ionic form of the contaminant and the electrochemical properties of the soil.

The interaction with soil organic matter is another layer of complexity that impacts bioremediation. Organic matter can form soluble or insoluble complexes with metals, influencing their transport and uptake by plants. For instance, while organic ligands can enhance metal mobility through chelation, excessive complexation may actually reduce bioavailability by immobilizing metals in stable forms (Benjamin et al., 2015). Moreover, organic matter also supports microbial activity, which is vital in microbe-assisted phytoremediation techniques. It enhances the proliferation of rhizobacteria and fungi that can alter metal speciation or promote root uptake through symbiotic interactions.

Soil texture, comprising the relative proportions of sand, silt, and clay, plays a role in metal sorption and percolation. Fine-textured soils (i.e., high in clay content) tend to have greater surface area and stronger adsorption capacity, potentially immobilizing metals and

limiting their availability. In contrast, sandy soils, due to lower adsorption capacity, may facilitate greater metal mobility but also pose risks of leaching contaminants into groundwater.

In light of these interactions, a one-size-fits-all approach to phytoremediation is impractical. Instead, successful application requires a nuanced understanding of site-specific soil characteristics and how these interact with both the contaminant type and the biological agent employed. Therefore, future research should integrate detailed soil profiling, including pH buffering capacity, redox conditions, and microbial diversity, to optimize remediation strategies tailored to local Philippine soils.

5.3 Environmental conditions

The environmental conditions of a bioremediation site—specifically temperature, soil moisture, and light availability—have profound effects on the success of both plant- and microbe-assisted remediation technologies (Yuniarti et al., 2022). These abiotic factors influence not only plant growth and health but also the physiological and biochemical processes that facilitate metal uptake, translocation, and detoxification. Similarly, for microbial bioremediation, environmental variables dictate microbial metabolism, survival, and the release of metabolites that can alter metal bioavailability (Vallalar et al., 2019).

In a controlled experimental study by Claveria et al. (2019a), it was observed that *Pteris melanocaulon*, a known arsenic hyperaccumulator, exhibited significantly reduced arsenic uptake under low-temperature conditions (below 20°C), even when the total arsenic concentration in the soil remained constant. At optimal temperatures (25–30°C), arsenic uptake in shoot tissues increased by nearly 40%, indicating that temperature not only affects transpiration rates but also enzyme activity and nutrient transport systems involved in arsenic absorption. This suggests that suboptimal temperatures may limit the plant's capacity to perform essential detoxification mechanisms, such as sequestration into vacuoles or conversion to less toxic forms. In field conditions, this underscores the importance of seasonal timing and site-specific thermal profiles in determining bioremediation efficacy.

Soil moisture content is another critical factor that directly impacts both plant and microbial performance. In the same study, Claveria et al. (2019b) noted that arsenic uptake peaked when soil moisture was maintained at 70–80% of field capacity. Below 50%, arsenic absorption declined sharply, likely due to reduced root elongation and lower arsenic solubility in drier soils. Furthermore, water stress was shown to hinder stomatal conductance and metabolic activity, ultimately diminishing translocation from roots to shoots. This highlights the need for active water management in phytoremediation projects, particularly in regions with pronounced dry seasons like many parts of the Philippines.

Building on this, Magsayo et al. (2023) investigated microbial-assisted phytoremediation under varying moisture and temperature regimes. Their study showed that rhizosphere bacteria significantly enhanced the uptake of nickel and cadmium only under moderate to high soil moisture levels and temperatures between 26–32°C. At lower temperatures, microbial activity decreased, leading to lower organic acid exudation and reduced solubilization of heavy metals. Similarly, excessive moisture created anoxic conditions, which suppressed aerobic microbial communities essential for metal transformation and uptake. These results reinforce the idea that both biotic and abiotic interactions must be optimized in tandem to maximize the efficiency of remediation systems.

Additionally, light intensity and photoperiod were found to indirectly influence metal uptake by modulating photosynthetic rates and energy availability in hyperaccumulator plants. While this factor was less emphasized in the reviewed studies, it remains an important consideration for in-situ applications, especially in areas with dense vegetation cover or variable shading patterns. Taken together, these findings point to a complex interplay between environmental conditions and bioremediation outcomes. Simply identifying a plant or microbe with potential for metal uptake is insufficient without understanding how environmental constraints can amplify or inhibit that potential. Thus, site-specific monitoring and environmental control—such as irrigation scheduling, shade management, and timing of planting—are essential to achieving consistent and scalable bioremediation results in the Philippine context.

5.4 Microbial interactions

Microbial interactions within the soil—particularly those involving the rhizosphere, the zone surrounding plant roots—are pivotal in enhancing both heavy metal uptake and plant resilience under contaminated conditions (Yuniarti et al., 2022). These interactions are not merely supportive but form a dynamic and reciprocal relationship that can determine the overall success of bioremediation. Mycorrhizal fungi, for example, extend the root's absorptive surface area through their hyphal networks, which enables plants to access metal ions and immobile nutrients from microsites that roots alone cannot reach. At the same time, beneficial soil bacteria such as *Pseudomonas*, *Bacillus*, and rhizobia engage in mechanisms like siderophore production, phosphate solubilization, and the secretion of organic acids—processes that alter metal speciation and increase bioavailability for plant uptake (Tansengco et al., 2018).

The study by Arellano et al. (2024) provides strong empirical evidence that microbial consortia not only mobilize metals through biochemical transformation but also induce systemic tolerance in plants by promoting antioxidant enzyme activity and reducing oxidative stress caused by heavy metal toxicity. These microbial inoculants, when present in sufficient density and diversity, act as biocatalysts that enhance phytoremediation efficiency beyond what plants can achieve alone. Additionally, microbial biofilms formed around root surfaces can modify pH and redox conditions locally, influencing the solubility and mobility of metals such as cadmium, nickel, and arsenic.

However, these plant-microbe interactions are highly context-dependent and influenced by a multitude of factors including soil type, contaminant concentration, root exudate composition, and microbial community structure. For instance, certain bacteria may facilitate arsenic reduction under anaerobic conditions, while others oxidize arsenite in aerobic environments, leading to different bioavailability outcomes. Moreover, the specificity between plant species and microbial partners means that beneficial effects observed in one system may not be replicable in another. This complexity necessitates further research to isolate optimal plant-microbe pairings and to develop microbial inoculants tailored to Philippine soils and contaminants.

To optimize bioremediation strategies, future studies must move beyond simple correlations and begin to untangle the mechanistic pathways through which microbes mediate metal mobility and plant stress response. Multi-omic approaches—such as metagenomics, transcriptomics, and metabolomics—could reveal the functional capabilities of soil microbiota in contaminated environments. This systems-level understanding could enable the design of more precise, synergistic bioremediation models that integrate microbial functionality with plant physiology and site-specific soil chemistry.

6. Limitations and Challenges Associated with the Application of Bioremediation Technologies for Heavy Metal Remediation

6.1 Bioavailability and uptake challenges

A primary challenge in bioremediation involves the limited bioavailability of heavy metals in soils (Castañares & Lojka, 2020). Only a fraction of the total metal content is accessible for plant uptake, which can significantly hinder remediation efforts (Cuevas & Banaay, 2022). Similarly, plant uptake limitations were observed in the results of Gotera et al. (2019), where the efficiency of metal uptake varied not only between species but also among individuals of the same species. This variability poses a considerable challenge to the general applicability of bioremediation across diverse contaminated sites (Claveria et al., 2019).

One key factor influencing bioavailability is the strong binding affinity of heavy metals to soil particles, especially in soils rich in clay or with high organic matter content. Metals such as lead and cadmium can form stable complexes with soil colloids, rendering them less mobile and difficult for plant roots to absorb. Moreover, the chemical form of the metal (speciation) significantly impacts its solubility and toxicity. For example, arsenate (As^{5+}) is more readily taken up by plants than arsenite, yet both can behave differently depending on soil redox potential and pH. These soil-dependent dynamics mean that a bioremediation strategy successful in one location may fail in another unless site-specific conditions are carefully considered and adjusted.

To overcome these limitations, researchers have explored the use of chelating agents and soil amendments to enhance metal mobility. Natural organic acids such as citric acid, as well as biodegradable chelants like EDDS, have been shown to temporarily increase metal solubility, thus improving uptake efficiency. However, this approach must be cautiously applied, as increased solubility can also lead to leaching of contaminants into groundwater if not properly managed. Recent field experiments have demonstrated that combining chelants with organic amendments—such as compost or biochar—not only improves bioavailability but also supports microbial communities that further assist in metal transformation and detoxification. These integrated approaches highlight the importance of adapting bioremediation practices to both the biological and physicochemical complexities of contaminated soils.

6.2 Plant and microbial tolerance

Another significant limitation in the application of bioremediation technologies is the variability in tolerance and accumulation capacity among different hyperaccumulator plant species (Sanchez & Cao, 2019). While certain plants are recognized for their exceptional ability to uptake specific metals, these traits are not universal and are often context-dependent. Benjamin et al. (2015) conducted a comparative study of three plant species—*Vetiveria zizanioides* (vetiver grass), *Pteris vittata*, and *Brassica juncea*—under similar heavy metal exposure conditions. Their findings revealed that *Pteris vittata* had high arsenic accumulation in fronds due to efficient translocation mechanisms, while *Brassica juncea* exhibited superior cadmium uptake but limited translocation to aerial parts. Vetiver grass, though highly tolerant to metal stress, accumulated significantly lower metal concentrations, suggesting its effectiveness may be more aligned with phytostabilization rather than phytoextraction.

These differences highlight that the success of phytoremediation depends not only on the presence of metal-accumulating traits but also on the match between a species' physiological characteristics and the specific type of contamination. For example, root architecture, transpiration rate, and metal-binding proteins like metallothioneins and phytochelatins can vary across species and heavily influence their remediation potential. Environmental variables such as pH, moisture, and light further modulate these traits, which may lead to inconsistent results across sites—even when the same species is used.

This variability in plant performance is paralleled in microbial-assisted remediation strategies. While microbial communities have demonstrated promising roles in enhancing metal solubility and uptake, their long-term viability and adaptability remain less predictable. Arellano et al. (2024) examined the behavior of metal-tolerant rhizobacteria over a prolonged exposure period and found that although some strains initially thrived and facilitated increased metal uptake by host plants, their population densities and metabolic activity declined over time. Factors such as nutrient depletion, accumulation of toxic intermediates, and shifts in soil pH and redox potential were shown to compromise microbial efficacy over extended durations.

Moreover, microbial communities are susceptible to genetic drift and environmental pressures, which may lead to reduced functional redundancy and a loss of critical traits needed for effective remediation. The uncertainty surrounding microbial adaptation under field conditions raises questions about the sustainability and consistency of bioaugmentation efforts. In some cases, introduced microbes may be outcompeted by native soil populations or fail to establish persistent colonies, thereby limiting their long-term impact.

Given these challenges, there is a growing need for comprehensive screening protocols that assess both short-term effectiveness and long-term resilience of bioremediating species—both plant and microbial. This includes evaluating genetic plasticity, stress response pathways, and interactions with other soil organisms. Integrative field trials that simulate real-world environmental dynamics, combined with longitudinal monitoring, would help refine selection criteria for candidate species and microbial strains.

6.3 Socio-economic challenges

Economic viability remains a critical barrier to the widespread adoption of bioremediation technologies (Aggangan et al., 2017). While it is often considered a cost-effective alternative to more aggressive remediation techniques, large-scale applications can be financially burdensome, especially when the cost of plant or microbial inoculants, monitoring, and maintenance are factored in (Cuevas & Banaay, 2022). Lastly, regulatory and public acceptance of bioremediation technologies pose non-technical but critical barriers to their implementation (Aba-Regis et al., 2021). Skepticism about the effectiveness and safety of using plants or microorganisms for remediation, alongside regulatory hurdles, can slow down or prevent bioremediation projects from being adopted.

One of the major financial challenges arises from the long timeframes needed for bioremediation to show measurable results. Unlike conventional methods such as soil excavation or chemical stabilization—which offer faster outcomes but at higher environmental and financial costs—bioremediation can take multiple planting cycles, especially in heavily contaminated sites. This extended timeframe increases operational costs related to labor, irrigation, site maintenance, and periodic testing. A study by Chen et al. (2020) comparing phytoremediation and chemical methods in lead-contaminated soils found that although phytoremediation was more environmentally sustainable, it

required at least 2–3 years to reduce soil lead concentrations to safe levels, whereas chemical methods achieved the same in months. However, phytoremediation proved 60% more cost-effective over a five-year period, especially when community involvement was integrated into monitoring and maintenance tasks. This highlights the importance of long-term planning and local stakeholder participation to enhance financial sustainability.

Beyond economic factors, regulatory inconsistencies and lack of public awareness further obstruct bioremediation implementation. In many developing countries, including the Philippines, existing environmental policies do not explicitly support or incentivize nature-based remediation methods. Moreover, public skepticism often stems from a lack of information or from prior unsuccessful pilot programs. According to Megharaj and Naidu (2017), increasing community engagement and establishing clear communication about the science, safety, and success stories of bioremediation are essential for building trust. Additionally, government support through subsidies, tax incentives, or the inclusion of bioremediation in national environmental cleanup frameworks could significantly improve its acceptance and adoption. Educational campaigns and collaborative partnerships with local governments, universities, and NGOs can also help shift public and institutional perception, making bioremediation a more viable and accepted solution for managing contaminated lands.

7. Implications of Applied Bioremediation Technologies

The review revealed that phytoremediation is the most frequently applied bioremediation technology in the Philippine context, observed in two-thirds of the selected studies. This method leverages hyperaccumulator plant species such as *Pteris melanocaulon* for arsenic and *Breynia cernua* for nickel to absorb and sequester heavy metals into harvestable plant parts. Its appeal lies in its eco-friendly nature and cost-effectiveness, particularly in low-resource settings. However, despite its potential, the practical implementation of phytoremediation across large and ecologically diverse contaminated areas presents several challenges. These include the limited tolerance and uptake efficiency of certain plant species, the sensitivity of plant growth to soil pH and contamination levels, and the slow pace of remediation, which may take several growing seasons to yield measurable results. Moreover, phytoremediation is not universally effective for all metals or all soil types, underscoring the need for more tailored, site-specific applications.

Complementing phytoremediation, microbial-based bioremediation strategies such as mycoremediation and bacterial remediation also demonstrate considerable promise. Fungal species like *Aspergillus* and cyanobacteria such as *Leptolyngbya* facilitate metal removal through biosorption, transformation, and the production of organic acids that alter metal speciation and solubility. However, the complexity of microbial communities and their sensitivity to environmental factors pose significant constraints. The effectiveness of microbial remediation is influenced by soil moisture, nutrient availability, temperature, and competition with native microbial populations. These conditions are often variable and difficult to control in field settings, which limits the generalizability of lab-scale findings.

To address these individual limitations, several studies advocate for integrated bioremediation approaches that combine plant-based and microbial-based strategies. Such synergy has been shown to enhance the overall uptake and tolerance capabilities of plants, particularly under adverse environmental conditions. Mycorrhizal fungi, for instance, extend the root absorption zone and improve plant access to both nutrients and metals in deeper soil layers. Similarly, cyanobacteria and other beneficial microbes can immobilize metals or convert them into less toxic forms, thereby reducing phytotoxic effects. These

interactions not only strengthen plant resilience but also increase the overall adaptability of bioremediation systems to diverse environmental settings. The successful implementation of such integrated strategies, however, depends on careful selection of compatible plant-microbe pairs, a deeper understanding of their interactions, and rigorous field trials that test their effectiveness at scale.

While phytoremediation is widely acknowledged as an environmentally viable strategy, field trials such as that of Chen et al. (2019) demonstrate the need for soil-specific selection of hyperaccumulators. In cadmium-contaminated loamy soils, *Brassica juncea* exhibited higher removal efficiencies than *Helianthus annuus*, but only under slightly acidic pH, emphasizing that soil pH and texture significantly affect metal uptake. Similarly, Albert et al. (2017) showed that fungal species' biosorption of metals like lead and cadmium decreased under arid conditions and high pH, suggesting microbial approaches are equally sensitive to soil variables.

Studies like Raklami et al. (2022) and Li et al. (2019) highlight that integrated remediation—combining plants with rhizobacteria or fungi—improves uptake efficiency and stress tolerance in plants, particularly when root zones are enriched with compatible microbes. Song et al. (2019), through a comparative experiment on four species, demonstrated that *Pennisetum* spp. and *Brassica* spp. excelled in phytoremediation under sandy loam soils with high organic matter, but uptake dropped in compacted soils. These studies confirm that bioremediation success is highly site- and species-dependent, and that primary experimental data is vital in identifying appropriate strategies tailored to specific environmental settings.

8. On Effective Application of Bioremediation Techniques

Effective application of bioremediation requires a nuanced understanding of the interactions between biotic agents and abiotic site conditions. Soil properties—such as pH, organic matter content, texture, and cation exchange capacity (CEC)—play a central role in determining the bioavailability of heavy metals. For instance, acidic soils tend to increase metal solubility and availability, whereas alkaline conditions can reduce mobility and uptake potential. Organic matter not only serves as a nutrient source for microbes but also contributes to improved soil structure, moisture retention, and aeration, all of which are critical for both plant growth and microbial activity. High CEC soils, meanwhile, are more capable of retaining positively charged metal ions, making them more available for uptake by plants and microbes.

Environmental factors such as temperature and soil moisture further influence the performance of bioremediation agents. As demonstrated in the study by Claveria et al. (2019a), arsenic uptake by *Pteris melanocaulon* decreased significantly under low-temperature and low-moisture conditions, even when soil arsenic concentrations remained constant. Similarly, Magsayo et al. (2023) found that microbial activity was optimal within a narrow temperature range of 26-32°C, with performance sharply declining outside these parameters. Soil moisture levels also directly affected enzymatic reactions and the mobility of metals in the rhizosphere. These findings emphasize the importance of managing site-specific conditions to optimize bioremediation outcomes.

Practical solutions to these environmental challenges include the use of soil amendments and irrigation systems tailored to the needs of the selected bioremediation strategy. Incorporating organic matter such as compost improves soil porosity and nutrient content, thereby supporting root expansion and microbial colonization. In addition, fertilizer application—particularly nitrogen, phosphorus, and potassium—can alleviate the stress

that contaminants impose on plants, allowing them to grow more vigorously and accumulate metals more efficiently. Controlled irrigation systems are particularly important in arid or drought-prone regions, where water scarcity may otherwise inhibit the success of bioremediating agents. By maintaining stable and suitable moisture levels, these systems enhance nutrient uptake, microbial metabolism, and overall remediation performance.

Soil amendments significantly affect metal mobility and microbial dynamics, as shown by Kumar et al. (2022), where compost addition enhanced microbial respiration and lead immobilization, while bentonite reduced metal solubility. Mahmood et al. (2020) found that loamy soils supported greater wheat biomass and cadmium uptake than sandy or clayey soils, especially under moderate irrigation—demonstrating how soil texture and water availability interact to influence remediation effectiveness. Similarly, Tordoff et al. (2000) observed improved metal extraction by *Festuca rubra* following compost amendment in a lead-contaminated field, validating organic matter's role in mobilizing or immobilizing metals based on context.

Cui et al. (2021) demonstrated that composted biosolids increased microbial diversity, improving heavy metal solubilization and promoting plant root colonization. Zhu et al. (2005) further showed that phosphate fertilizers reduce bioavailable lead in alkaline soils by promoting metal precipitation. These findings reinforce that effective bioremediation requires experimental determination of how soil chemistry interacts with applied amendments and environmental parameters.

9. Addressing Limitations and Challenges in the Application

Despite the demonstrated potential of bioremediation, its broader implementation is limited by several technical, biological, and socio-economic challenges. One of the most persistent technical obstacles is the low bioavailability of heavy metals in contaminated soils. Often, these metals are tightly bound to soil particles and exist in forms that are inaccessible to plants and microbes. This limitation significantly reduces the effectiveness of phytoremediation and microbial remediation efforts. To overcome this, chelant-assisted remediation has been introduced, using compounds such as ethylenediaminetetraacetic acid (EDTA) to mobilize metals and make them more accessible. While synthetic chelants are effective, they pose risks of leaching metals into groundwater and are not readily biodegradable. Therefore, recent research favors natural alternatives like citric acid and humic substances, which offer similar mobilization benefits with reduced environmental impact.

Biological limitations also restrict the reliability and scalability of bioremediation. Not all hyperaccumulator plants or microbial strains demonstrate consistent performance across different environments. The study by Benjamin et al. (2015) revealed substantial variability in metal uptake capacities among plant species, influenced by their physiological traits and the surrounding soil conditions. Moreover, Arellano et al. (2024) found that microbial strains introduced for remediation often exhibit a decline in metabolic activity over time, particularly in nutrient-poor or fluctuating field environments. These findings suggest that long-term adaptation remains a critical uncertainty in microbial-assisted remediation. Identifying resilient plant-microbe combinations and developing locally adapted strains are therefore essential to improving effectiveness under field conditions.

Beyond technical and biological concerns, socio-economic and regulatory challenges further complicate the adoption of bioremediation. Although it is often promoted as a cost-effective solution, implementation entails considerable expenses related to monitoring, maintenance, and specialized inputs. In resource-constrained settings like the

Philippines, such costs can be prohibitive. Additionally, public skepticism about the reliability of bioremediation, coupled with the absence of clear regulatory frameworks and government incentives, reduces the willingness of landowners and local governments to invest in these technologies.

A more sustainable pathway involves community-driven bioremediation programs that engage local residents in the management and monitoring of projects. As shown by Mahanayak (2024), these initiatives lower operational costs and increase local ownership, thereby enhancing long-term viability. Megharaj and Naidu (2017) similarly emphasized the benefits of training communities to identify remediation species, monitor progress, and participate in decision-making processes. On a policy level, governments can play a transformative role by offering subsidies, grants, or tax incentives to encourage the adoption of bioremediation techniques (Catacutan et al., 2012). Educational campaigns are also essential to counter public misconceptions and promote wider acceptance. These initiatives can highlight the ecological and economic benefits of bioremediation, especially in restoring agricultural productivity and improving environmental health. Together, these community-based and policy-driven strategies can help overcome the practical barriers to effective bioremediation and support its integration into mainstream environmental management.

Addressing metal bioavailability remains a major challenge, particularly when metals are bound tightly to soil matrices. Evangelou et al. (2007) demonstrated that citric acid outperformed EDTA in mobilizing copper and nickel without causing groundwater leaching, especially under neutral pH. In contrast, the said compound was persistent and risked contaminating adjacent water bodies. This indicates that biodegradable chelants should be prioritized in practical applications, particularly in high-risk or agricultural zones.

Microbial adaptability is also a limiting factor. Wei et al. (2023) conducted a three-year field study showing that *Rhizobium* inoculants declined in activity after one year without continued nutrient input or re-inoculation. Similarly, Sharma et al. (2025) found that microbial consortia performed better than single strains, particularly under metal stress, suggesting resilience may be improved by using mixed cultures. Lei et al. (2021), in a long-term field trial, reported fluctuating zinc uptake in *Solanum nigrum* due to seasonal variability and microbial shifts, further underscoring the need for sustained monitoring.

Economically, phytoremediation offers advantages in low-income regions. Chen et al. (2019) conducted a comparative economic study and found that phytoremediation, while slower, was 60% more cost-effective than chemical methods over a 5-year period. These findings support the inclusion of long-term cost-benefit analyses when planning remediation, especially in the Philippines where resource constraints and agricultural land recovery are critical considerations.

10. Conclusions

This systematic review evaluated the current bioremediation technologies applied to heavy metal-contaminated soils in the Philippines, revealing the potential of phytoremediation, mycoremediation, bacterial, and cyanobacterial bioremediation. The studies reviewed primarily focused on areas impacted by mining activities, with copper, nickel, lead, and arsenic being the most common contaminants. The findings demonstrate that bioremediation is a viable, environmentally friendly, and cost-effective approach for soil remediation in the country. However, the effectiveness of these technologies is highly influenced by biological traits, soil properties, environmental conditions, and microbial interactions, which highlights the need for tailored, site-specific strategies.

Despite these promising results, several limitations exist. The bioavailability of heavy metals remains a challenge, as not all metals are accessible for uptake by plants and microorganisms. Furthermore, there is significant variability in metal uptake capacity among species, which limits the scalability of bioremediation efforts. Socio-economic barriers, including the cost of implementation and maintenance, as well as regulatory challenges, also hinder the widespread adoption of these technologies.

Future research should focus on integrating plant-microbe systems to enhance metal uptake and improve overall bioremediation efficiency. Field trials in real-world settings are essential to validate laboratory findings and explore the scalability of these technologies. Additionally, natural chelating agents and community-driven bioremediation programs could address both the technical and financial challenges of bioremediation. With this, bioremediation can become a more reliable and sustainable solution for managing heavy metal contamination in the Philippines and beyond.

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12. Authors' Contributions

Cyril John C. Nagal designed and performed research; and Badi R. Samaniego coordinated and performed research.

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13. Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this study.

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