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Enhancing phytoremediation of heavy metals: A comprehensive review of performance microorganism-assisted *Cyperus rotundus* L.

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ABSTRACT

Cyperus rotundus L is a hyperaccumulator plant for decomposing heavy metals. High heavy metal content can inhibit its growth, thus reducing its removal efficiency. Using microorganisms in the phytoremediation process will likely improve their performance in decomposing heavy metals and increase their growth. This review aims to synthesize the current knowledge on the performance of microorganism-assisted *Cyperus rotundus* L. in the remediation of heavy metal-contaminated environments, highlighting this approach's key factors, mechanisms, and potential applications. The investigation used the PRISMA framework, which stands for systematic review and meta-analysis. The search was conducted using various online databases, Scopus, using a combination of keywords, including "*Cyperus rotundus*", "phytoremediation", "heavy metals", "plant growth-promoting rhizobacteria" and "microorganism-assisted." The process involved identifying the research question, selecting relevant studies, tabulating results, and summarizing findings. Results indicate that *Cyperus rotundus* L. has quite a good ability in the remediation of heavy metals such as sulfate, Cd, Pb, Mn, Cu, Fe, and Cr. Although it can grow in extreme environments, high concentrations of heavy metals can reduce its photosynthetic ability and cause death. Using microorganisms on plants can help plants increase their effectiveness in removing heavy metals. Microorganisms play a role in plant growth promotion, heavy metal solubilization and chelation, and the elimination of metal-induced stress. Further research is needed to understand the complexities of these plant-microbe interactions fully and to optimize the application of this technology for large-scale environmental remediation.

Keywords: *Cyperus rotundus* L., heavy metals, microorganism, phytoremediation.

INTRODUCTION

Heavy metal (HM) contamination of the environment is a significant global concern, with widespread implications for human health and ecological balance (Hayyat et al., 2023). Commonly, HMs are classified into essential and non-essential. Essential HMs (e.g., Fe, Zn, Cu, and Mn) are needed by living things in small amounts and toxic in high concentrations, while non-essential HMs (e.g., P, Hg, Cd, As, and Cr) are toxic and unnecessary for biological function. HMs are known is dangerous because their resistance to degradation and can accumulate in the soil over extended periods. Furthermore, it can accumulate in soil and water, contaminate the food chain, and negatively impact the health of living things, including humans. Therefore, actions to control the negative impacts caused by HM pollution are needed. One of them is the remediation process.

The remediation process play role to decreases the concentration of HMs in the environment.

It is an active method of cleaning up a polluted environment and plays a role in preventing the bioaccumulation of HMs in living things through the food chain. Nowadays, remediation is widely applied in physical, chemical, and biological forms. Physical and chemical remediation are commonly used in HM control. However, they have limitations such as high costs, soil damage, chemical residue persistence, and the possibility of HM release from soil particles due to environmental changes. Further, biological remediation, using plants to remove HMs is more effective (Thomas et al., 2022). It is known as Phytoremediation.

Phytoremediation is a process of removing pollutants using hyperaccumulator plants. Unlike traditional remediation, which uses hazardous chemicals, phytoremediation offers an eco-friendly approach. Commonly, phytoremediation mechanism includes phytoextraction, phytostabilization, phytovolatilization, phytodegradation, and rhizodegradation (Banda et al., 2024). In phytoextraction, hyperaccumulator plants are used to absorb toxic metals from the soil and store them in the above-ground parts (Khilji et al., 2024). Meanwhile, phytostabilization utilizes plants to prevent the spread of pollutants by binding them in the roots. Additionally, in phytodegradation involves the uptake of organic pollutants by roots and breakdown them into harmful substances. Plants also absorb organic materials from the environment and convert them into gases that are released into the atmosphere through transpiration by phytovolatilization (Banda et al., 2024). Among the various plant species explored for phytoremediation, the sedge *C. rotundus* L. has shown potential for the uptake and accumulation of heavy metals in contaminated environments. *C. rotundus* L. (*Cyperus*) is one of the plants with hyperaccumulation properties (Ariyachandra et al., 2023; Wang et al., 2010) and has performance in uptake and accumulation of HM (Ariyachandra et al., 2023). This plant can grow well in extreme environmental conditions and has high productivity (Wang et al., 2010). However, the high concentration of HM can inhibit their growth and HM's removal efficiency. Therefore, the efficiency of phytoremediation can be further enhanced through the integration of microorganisms.

Microorganisms play a role in increasing phytoremediation's ability to absorb pollutants, thereby accelerating the remediation process. This method also forms chelation agents, thereby increasing plant resistance to HM exposure and the ability of plants to translocate and accumulate HMs. Further, microorganisms can produce plant growth-promoting substances, solubilize heavy metals, and alleviate metal-induced stress in the host plant, ultimately resulting in greater heavy metal accumulation in the plant biomass (Gupta et al., 2019). Additionally, symbiotic associations between plant and fungi, such as arbuscular mycorrhizal fungi, can further enhance the plant's access to nutrients and water, as well as its tolerance to heavy metals (Gupta et al., 2019; Muthusaravanan et al., 2020; Wani et al., 2017). Furthermore, rhizodegradation uses plant roots to stimulate the activity of microbes and fungi in the root zone (rhizosphere) to break down organic pollutants (Banda et al., 2024).

This comprehensive review aims to synthesize the current state of knowledge on the performance of microorganism-assisted *C. rotundus* L. in the remediation of heavy metal-contaminated environments, highlighting the key factors, mechanisms, and potential applications of this approach. The use of microorganisms in conjunction with *C. rotundus* can lead to improved phytoremediation outcomes by enhancing the plant's ability to uptake, translocate, and detoxify heavy metals.

RESEARCH METHODS

This literature review employed a systematic approach using a meta-analysis research method. To evaluate the performance of microorganism-assisted *C. rotundus* L. in the phytoremediation of heavy metals, a comprehensive literature review was conducted. The search focused on peer-reviewed articles published in reputable scientific journals, with a particular emphasis on studies that explored the following aspects:

1. The ability of *C. rotundus* to accumulate and tolerate heavy metals in contaminated environments.
2. The role of plant growth-promoting microorganism in enhancing the phytoremediation efficiency of *C. rotundus.*
3. The synergistic effects of *C. rotundus* and associated microorganisms in the remediation of heavy metal-polluted sites.

The search was conducted using various online databases Scopus, using a combination of keywords, including "*Cyperus rotundus*", "phytoremediation", "heavy metals", "plant growth-promoting rhizobacteria", and "microorganism-assisted". To support the hypothesis aimed at enhancing the conceptual understanding of the research data, several key steps were undertaken in writing the review. These steps included identifying the research question, selecting relevant studies, choosing appropriate studies, tabulating the findings, and summarizing and reporting those findings (Analita et al., 2023). The analysis utilized a systematic review and meta-analysis framework known as PRISMA, as illustrated in Figure 1.

A total of 480 articles (review and research article) were identified through a search of journals in the Scopus database with criteria of article years is 2022–2024. After reviewing these articles, 137 articles with type research article were selected in the identification step, focusing specifically on research articles. During the screening phase, obtained 31 articles related to the role of microorganisms in the phytoremediation process, specifically using *C. rotundus* as an agent. In the advanced screening phase, 19 articles were removed after a full-text review, finally checking it down to the specific topic. In the end, 12 articles met the eligibility criteria based on perceived relevance. The selection of final articles is based in a comprehensive analysis of the substance and its relevance to the research theme. Data extraction using NVivo 12 Plus. A credibility test to ensure the validity of data using the triangulation approach.

The selected articles focus on understanding the performance of microorganism-assisted *C. rotundus* L. in the remediation of heavy metal. This review serves as a basis for further research about the important role of the implementation of microorganism-assisted *C. rotundus* L. in the phytoremediation of HMs. This analysis presents recent findings that support the concept of phytoremediation, explains highlighting the key factors, mechanisms, and potential applications of this approach.

RESULT AND DISCUSSION

The ability *Cyperus rotundus* L. to accumulate heavy metals

C. rotundus L., commonly referred to as coco grass, nut grass, nut sedge, or java grass, is a persistent perennial weed known for its highly adaptive nature and the challenges it poses in eradication. This invasive weed is notorious for its rapid and aggressive spread due to its robust rhizome system. The findings from the literature review indicate that *C. rotundus* L. is a promising candidate for the phytoremediation of heavy metals (Table 1). The plant has demonstrated the ability to accumulate significant concentrations of heavy metals, such as lead, cadmium, and chromium, in its various tissues. *C. rotundus* has been found

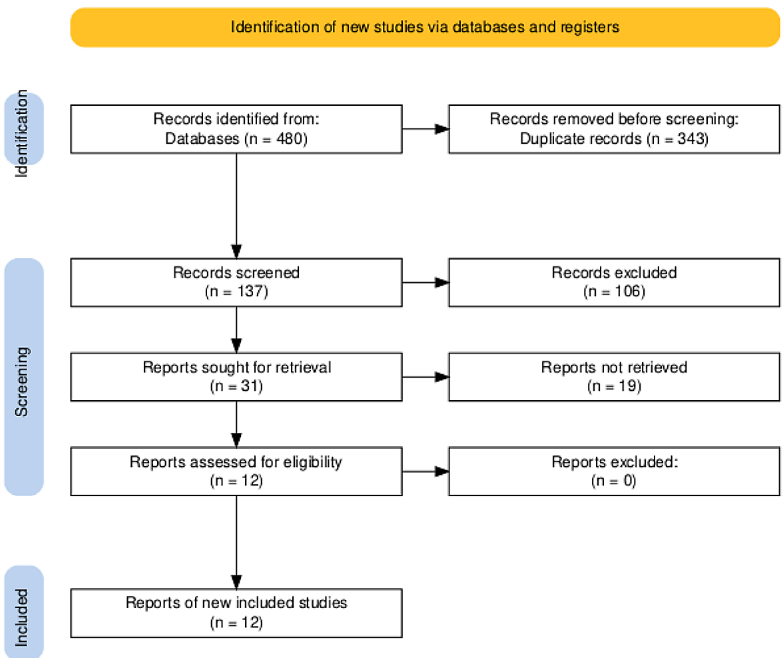

Figure 1. The meta-analysis framework (PRISMA)

to have a positive impact on soil quality in areas with a lot of plant life. It can improve soil fertility and the availability of nutrients, ultimately leading to better soil quality (Ngongo et al., 2022).

According to Table 1, *C. rotundus* can function as a phytostabilizer for metals like Mn and Cu, a hyperaccumulator for Sn, As, Cd, and Ni stabilizer. In phytoremediation, BAF, BCF, and BTF are crucial metrics used to assess a plant's ability to uptake and handle contaminant. BAF and BCF used to aseesses the accumulation of contaminants in plant tissues, whereas BTF is used to quantifies the plant's ability to move contaminants from its roots to uts above-ground area (shoots, leaves, stems) (Rodrigo et al., 2024). The studies have identified it as a potential hyperaccumulator plant for phytoremediation, because their BAF, BCF, and BTV value > 1. The long-term impacts of employing *C. rotundus* for HM control have not been explicitly traced. However, *C. rotundus* has been identified as a possible agent for detoxifying HMs, and specifically, it functions as a stabilizer for metals. It is evident from its capacity to accumulate HMs in its roots and transfer them to above-ground tissues. Despite its potential for detoxification, *C. rotundus* is also considered a troubling plant in agriculture due to its invasive characteristics and adverse effects on crop yield (Yan et al., 2020). It causes economically damaging, Competition interference in crop production, allelopathic interference in crop production, and interference as an alternative host for insect pests and diseases, causing 20–90% yield losess in more than 50 crops, such as rice, maize, and sugarcane (Peerzada, 2017). The uncontrolled spread of water hyacinth can blanket the water surface, block sunlight from penetrating the water, lead to shallowing and blockage of water channels, irrigation interfere and obstruct water transportation activities. Table 2 shows their performance in the remediation of HM.

According to Table 2, *Cyperus rotundus* L. has shown promising results in removing metals such as Fe, sulfate, Cd, Pb, and Cr from contaminated environments. *C. rotundus* has a high removal efficiency of sulfate, Cd, and Pb > 50%, however, for Fe and Cr, their removal efficiency is < 50%. This indicates that *C. rotundus* performs better in removing sulfate, Cd, and Pb compared to Fe and Cr. However, based on the root BAF values > 0.5, confirming the plant is effective as a phytoremediation agent. The efficiency of *C. rotundus* L. in metal removal can be attributed to its various phytoremediation mechanisms, including bioaccumulation, translocation, and rhizofiltration. The effectiveness of *C. rotundus*

Table 1. The role of *Cyperus rotundus* as phytoremediation agent

No	Alternative conceptions	Theoretical conception	Source
1	*Cyperus rotundus* has potential as a phytoremediation agent for Mn compounds	*Cyperus rotundus* is a hyperaccumulator plant proficient in decomposing heavy metals, particularly manganese (Mn). The results indicated that the bioaccumulation factor (BAF), bioconcentration factor (BCF), and translocation factor (BTF) values > 1, confirming the plant's effectiveness as a phytoremediation agent	(Rodrigo et al., 2024)
2	*Cyperus rotundus* is a hyperaccumulator plant	This plant is able to remove 45% Cu at T1. The addition of microorganisms can increase the ability of *C. rotundus* to remove Cu. This plant is also able to remove As, Cd, Cu, Ni, and Pb (> 60%)	(Velasco-Arroyo et al., 2024)
3	The use of *Cyperus rotundus* as a phytoremediation agent and wetland has no negative impacts	*C. rotundus* is effective in removing COD, BOD, TSS, turbidity, and phosphate with efficiency levels of 70, 79, 90, 96, 64, 82, 92, and 48%, respectively	(Imron et al., 2024)

Tabel 2. The HM's phytoremediation performance of *C. rotundus* L.

Metal	Before treatment	After treatment	Removal efficiency (%)	Root BAF	Ref.
Fe (mg/Kg)	16596.338	16014.146	3.51	-	This study
SO_4 (ppm)	2059.99	378.775	81.61	0.702	This study
Cd (mg/Kg)	0.04	0.01	75.00	0.750	(AL-Huqail et al., 2023)
Pb (Mg/Kg)	0.06	0.01	83.33	0.670	(AL-Huqail et al., 2023)
Pb	0.045	0.0195	56.67	> 1	(Nwaichi et al., 2021)
Cr	0.375	0.228	39.20	> 1	(Nwaichi et al., 2021)

in remediating polluted soils may vary depending on the specific HMs present and the kind of other plant coexistence in the environment (Wei et al., 2021). Moreover, environmental conditions include pH, an initial contaminant concentration, contact time, and temperature, which increase their efficiency (AL-Huqail et al., 2023). The role of pH in plants absorption of metals is very important because soil pH affects metal speciation, solubility, mobility and bioavailability for plants. Reducing pH of the soil increases the desorption and dissolution of HMs in the soil solution, improving the absorption of metals by plants. Plants modify the root environment by emitting protons, affecting ion uptake and nutrient uptake. pH of 6 to 7.5 is ideal for maximizing the growth of *Cyperus rotundus* and promoting the activity of microorganisms (Adamczyk-Szabela and Wolf, 2022; Zeng et al., 2011). Whereas higher temperatures (20 °C and 30 °C) may increase plant growth and microbial decomposition rates, leading to enhanced contaminant uptake and breakdown.

The role of microorganism-assited phytoremediation of *Cyperus rotundus*

Phytoremediation is one of the methods that can be used for the HM's remediation using plants. However, high HM content in the soil, such as Cd, Cr, and Pb, can reduce their ability in the photosynthesis process and cause reduce their ability to growth and development. In addition, the HM's content also significantly affects the phenotypic properties of plants. Rhizosphere interactions and the dynamics of microbial communities play a crucial role in the success of microbial-assisted phytoremediation using *C. rotundus* L. (Liu et al., 2022). Soil bacterial communities have been found to differ significantly between the rhizospheres of different plant species, including *C. rotundus*, Robinia pseu-doacacia, and Alyssum murale, growing in metal-contaminated environments (Gupta et al., 2019). Studies have reported that the dominant bacterial genera in the rhizosphere of *C. rotundus* include *Gemmatimonas, Sphingomonas, Bradyrhizobium*, and *Ellin6067*, which have been associated with the plant's ability to tolerate and accumulate heavy metals (Liu et al., 2022). Therefore, the role of microorganisms is very important in supporting the phytoremediation process.

The mechanisms by which microorganisms can enhance the phytoremediation performance of *Cyperus rotundus* can be broadly categorized into three main aspects (Asad et al., 2019; Gupta et al., 2019):

1. Plant growth promotion: Microorganisms can secrete various plant growth-promoting substances, such as auxins, cytokinins, and gibberellins, which can stimulate the growth and development of *C. rotundus* (Asad et al., 2019). This enhanced plant growth can lead to increased biomass production and, consequently, greater heavy metal uptake and accumulation.
2. Heavy metal solubilization and chelation: Certain microorganisms can produce organic acids, siderophores, and other metabolites that can solubilize and chelate heavy metals, making them more bioavailable for uptake by the plant.
3. Alleviation of metal-induced stress: Microorganisms can also help mitigate the adverse effects of heavy metals on *C. rotundus* by producing antioxidants, osmoprotectants, and other stress-relieving compounds, as well as by modulating the plant's defense responses.

These mechanisms work in synergy to enhance the overall phytoremediation performance of *C. rotundus*, leading to increased heavy metal uptake, improved plant growth and biomass, and greater tolerance to metal-induced stress (Asad et al., 2019; Gupta et al., 2019).

According to Table 3, inoculating microorganisms in the phytoremediation process enhances their effectiveness. Microorganisms play a crucial role in promoting plant growth and optimizing the capacity of plants to adsorb and detoxify heavy metals (HMs) in contaminated soil (Ma et al., 2011). Research by Qadir et al. (2024) indicates that the inoculation of *A. bouvetii* in plants leads to an increase in net assimilation rate (NAR) and relative growth rate (RGR), along with heightened production of indole-3-acetic acid (IAA) and modulation of lipid content. Additionally, it contributes to increased reactive oxygen species (ROS) scavenging and boosts the activity of catalase, superoxide dismutase, peroxidase, and other enzymes. Furthermore, levels of flavonoids, phenolics, proline, and glutathione are also elevated. This makes *A. bouvetii* is a key collaborator in enhancing plants' resistance and tolerance to arsenic. Consequently, it emerges as a strong candidate for microorganisms that improve phytoremediation performance, particularly with respect to arsenic.

Table 3. The role of microorganism-assisted in phytoremediation process

No	Alternative conceptions	Theoretical conception	Source
1	The plants (African marigold or *Tagtes erecta* L.) treated with *S. stutzeri* and *P. sundara* absorb high concentrations of HM's	Plants, together with microorganisms, showed great performance for the HM's phytoremediation process. Plants showed an increase in biomass, protein, and chlorophyll levels, indicating their efficacy in detoxifying HMs. The addition of microorganisms to plants also strengthened plant defenses, reduced oxidative stress, increased antioxidant activity, and improved their ability to combat contamination	(Khilji et al., 2024)
2	The use of inoculum in the phytoremediation process can reduce HM's levels	The use of inoculum in the phytoremediation process affects the structure of the soil community and increases the diversity and complexity of bacteria. The addition of bacterial inoculum can also improve soil quality	(Wu et al., 2024)
3	Inoculation of Acinetobacter bouvetii on sunflowers can improve its performance in accumulating As (Arsenic)	The use of A. buoveti can reduce stress on sunflowers. This strain can absorb and strain arsenic well, so it can be applied for phytoremediation	(Qadir et al., 2024)
4	A combination of plants and rhizobacteria is able to detoxify leachate	The use of rhizobacteria in the reactor (*Bacillus cereus, Nitrosomonas communis,* and *Pseudomonas aeruginosa*) in plants can increase their ability to detoxify leachate. Phytodetoxification results show plant efficiency ranging from 40–70%. The addition of rhizobacteria bioaugmentation to plants can detoxify COD. BOD, TSS, TN, Cd, and Hg more than 70%	(Arliyani et al., 2023)
5	The use of root-associated microbiomes in hyperaccumulator plants can increase plant growth and metal accumulation	A study on Athyrium wardii, a phytostabilizer, preventing the movement and leaching of metals into groundwater, in lead-zinc mine tailings, found that the root-associated microbiome assembly significantly promotes plant growth and metal accumulation. The bacterial community assembly was non-random and shaped by root-selective effects. The dominant bacterial phyla were *Proteobacteria, Chloroflexi, Actinobacteria, Cyanobacteria,* and *Acidobacteriota*. Rhizosphere soil and endosphere enriched with functional categories, contributing to metal solubility and bioavailability. Membrane transporters, particularly ATP-binding cassette transporters, were enriched in the endosphere, suggesting potential roles in metal tolerance and transportation	(Zhang et al., 2024)

The results obtained by Khilji et al. (2024) also indicate similar findings. The inoculation of *S. stutzeri* and *P. Sundara* during the HM detoxification process using *Tagetes erecta* L. showed a positive correlation. This inoculation not only enhances the plant's defenses but also reduces oxidative stress, increases antioxidant activity, and boosts the plant's ability to combat contamination. Further, the involvement of these microorganisms has been shown to improve plant performance in HM detoxification, characterized by increased biomass, protein, and chlorophyll levels. Specifically, the roots of *T. erecta* inoculated with *S. stutzeri* exhibited a 17% and 19% increase in cadmium concentration at 5% and 10% contamination levels, respectively. In contrast, when inoculated with *P. Sundara*, there was an increase in cadmium levels of 3% and 8% at the same contamination levels compared to the control.

The integrating microorganisms into the plant media is known to enhance growth hormones, produce siderophores, and increase the production of antioxidant enzymes in plants (Sharma et al., 2020).Through processes including nitrogen fixation, phosphate solubilisation, siderophore synthesis, phytohormone secretion, and ACC deaminase activity to lessen stress, the bacteria promote plant growth (Xu et al., 2018). Furthermore, bacteria produce biofilms that improve nutrient exchange, pollutant breakdown, and metal toxicity by establishing a protective microenvironment (Mishra et al., 2022). While lowering the absorption of harmful metals like arsenic and cadmium, metal-tolerant bacteria such as *Pseudomonas* sp., *Bacillus vietnamensis*, and *Kocuria flava* encourage plant development (Ren et al., 2023). By focussing on genes important in metal absorption, transport, and detoxification, CRISPR technological advancements further improve phytoremediation. Examples include giving plants transporter proteins and metal-binding proteins (such as metallothioneins and phytochelatins) (Ma et al., 2011).

Apart from bacteria, fungi can be used in mycoremediation to purify toxic materials in water and soil. Arbuscular mycorrhizal fungi (AMF) and *Exophiala pisciphila* are two examples of fungi that might lessen the toxicity of HMs like cadmium (Cd) by improving nutrient absorption, reducing metal buildup in crops like rice, and activating antioxidant mechanisms (Li et al., 2020; Wang et al., 2016). According to Li et al. (2023), Trichoderma fungus have shown great promise in detoxifying HMs like chromium while also promoting plant growth, soil fertility, and pathogen control. In addition to being very successful in eliminating HMs from wastewater, entomopathogenic fungi such as Beauveria bassiana also function as environmentally benign biopesticides (Gola et al., 2016). By minimising dependency on traditional chemical treatments and promoting ecologically friendly agriculture, these fungi provide sustainable solutions for HM contamination through bioabsorption and bioaccumulation.

Furthermore, endophytes have a direct impact on phytoremediation by secreting substances that help plants absorb nutrients and detoxify HMs (Khatoon et al., 2024b). To facilitate phytostabilization, endophytic bacteria generate organic acids to activate HM ions, siderophores to boost iron availability, and biosurfactants to increase metal solubility in soil. Additionally, certain endophytes can fix nitrogen and solubilise phosphorus, which enhances plant growth and health in polluted soil (Carlos et al., 2016). Furthermore, endophytes could alter the soil environment to improve overall plant resilience while secreting phytohormones, antioxidant enzymes, and exopolysaccharides (EPS) that lessen the toxicity of HMs (Carlos et al., 2016). Indirect consequences of endophytes include producing systemic resistance in plants, which increases tolerance to oxidative stress from HMs, and competing with other microorganisms for resources and space (Khatoon et al., 2024a). Through adsorption and chelation, endophytes can also change the valence state of HMs, lowering their toxicity and mobility in the soil. Furthermore, endophyte-induced modifications to root shape encourage plant development in very contaminated areas (Belimov et al., 2005). *Serratia marcescens* and *Pseudomonas* sp. are two endophytes that help detoxify polluted soil by increasing the volatilisation of HMs like mercury (Ma et al., 2016).

The integration of *C. rotundus* L. with plant growth-promoting rhizobacteria has shown great promise in the remediation of heavy metal-contaminated environments. One such strategy involves the use of a consortium of microbes that can work synergistically to enhance the phytoremediation capabilities of *C. rotundus*. Another approach is the use of genetically engineered microbes that can further improve the plant's heavy metal uptake and tolerance, leading to more efficient and rapid remediation of contaminated sites. When combined with appropriate agronomic practices, such as soil amendments and nutrient management, the microbial-assisted phytoremediation using *C. rotundus* L. can be a cost-effective and environmentally friendly solution for the remediation of heavy metal-contaminated environments.

The synergistic *Cyperus rotundus* and microorganisms in the remediation of heavy metals

Numerous studies have demonstrated the effectiveness of microorganism-assisted phytoremediation using *C. rotundus*. Plant growth-promoting rhizobacteria have been shown to enhance the uptake and translocation of heavy metals in *C. rotundus*, as well as alleviate the adverse effects of metal stress on the plant (Asad et al., 2019; Gupta et al., 2019). These beneficial microbes can produce growth hormones, organic acids, and other metabolites that improve plant growth and overall productivity, ultimately leading to greater heavy metal accumulation in the plant biomass. Additionally, certain fungi, such as arbuscular mycorrhizal fungi, have been found to form symbiotic associations with *C. rotundus*, increasing the plant's access to nutrients and water, and enhancing its ability to tolerate and accumulate heavy metals

The use of microbes in the phytoremediation process involving *C. rotundus* is expected to enhance the production of siderophores. These are well-known iron-chelating agents produced by various microbes associated with the rhizosphere. Siderophore-producing microbes are eco-friendly and sustainable, helping to manage plant stress in degraded lands. Additionally, incorporating plant growth-promoting bacteria (PGPB) and arbuscular mycorrhizal fungi (AMF), such as *Acinetobacter bouvetii, Bacillus cereus, Nitrosomonas communis, Pseudomonas aeruginosa, Sinorhizobium stutzeri,* and *Pseudomonas sundara*, is anticipated to improve the capacity of *Cyperus rotundus* to decompose heavy metal levels in contaminated soil.

Microorganisms such as *Acinetobacter bouvetii* and *Pseudomonas aeruginosa* can dissolve heavy metals that are bound to soil particles by producing organic acids and siderophores. These siderophores not only bind iron but also other heavy metals, which makes them more easily absorbed by the roots of *C.rotundus*. Plant growth-promoting bacteria (PGPB) like *Bacillus cereus* and *Pseudomonas* species can produce growth hormones, fix nitrogen, and solubilize phosphates, all of which stimulate the growth of *C. rotundus*. Healthy plant growth is essential for increasing the capacity for metal absorption. Some microorganisms can transform heavy metals into less toxic forms through reduction or oxidation processes. For example, *Pseudomonas* species can reduce heavy metal ions into less soluble forms. However, further research is needed to understand how *C. rotundus* responds to the inoculation of these microorganisms in terms of heavy metal detoxification.

The integration of plant growth-promoting rhizobacteria with *C. rotundus* has been shown to enhance the phytoremediation efficiency of the plant. These microorganisms can help alleviate heavy metal-induced stresses, promote plant growth and biomass production, and increase the uptake and translocation of contaminants from the roots to the aboveground biomass. The studies reviewed have highlighted the synergistic effects of *C. rotundus* and associated microorganisms in the remediation of heavy metal-polluted sites. The plant's ability to thrive in a wide range of environmental conditions, coupled with the support of plant growth-promoting bacteria, make *C. rotundus* a promising and eco-friendly solution for the remediation of heavy metal-contaminated ecosystems (Asad et al., 2019; Gupta et al., 2019; Wani et al., 2017). However, it is important to note that the success of microorganism-assisted phytoremediation with *C. rotundus* may depend on various factors, such as the type and concentration of heavy metals present, the specific plant-microbe interactions, and the environmental conditions of the contaminated site. These factors can significantly influence the overall effectiveness of this approach.

To further optimize the performance of microbial-assisted phytoremediation using *C. rotundus L.*, several factors should be considered:

1. Screening and selection of highly efficient plant growth-promoting rhizobacteria: Extensive screening and characterization of diverse microbial strains can help identify the most effective ones for enhancing the phytoremediation capabilities of *C. rotundus*.
2. Genetic engineering and synthetic biology approaches: Genetic manipulations of *C. rotundus* or its associated microbes can potentially improve specific traits, such as heavy metal uptake, tolerance, and biomass production, leading to enhanced remediation outcomes.
3. Optimization of environmental conditions: Careful management of soil properties, nutrient availability, and other environmental factors can create the optimal conditions for the growth and performance of both the plant and the microorganisms

Challenges and limitations of heavy metal phytoremediation

Despite the promising potential of *C. rotundus* in heavy metal phytoremediation, there are several challenges and limitations that need to be addressed. One of the main challenges is the slow growth and limited biomass production of this plant, which can limit its overall remediation efficiency (Gupta et al., 2019). Additionally, the high stress imposed by heavy metals can adversely affect the plant's growth and performance, potentially reducing its phytoremediation capacity. To overcome these limitations, the integration of microorganisms can play a crucial role in enhancing the growth, metal uptake, and stress tolerance of *C. rotundus*. Microorganisms can directly improve the plant's performance by producing plant growth-promoting substances, solubilizing and chelating heavy metals, and mitigating metal-induced stress. Furthermore, the use of microbial consortia, rather than single strains, can provide a more comprehensive and synergistic approach to enhancing phytoremediation. Despite these challenges, the continued research and optimization of microbial-assisted phytoremediation using *C. rotundus* L. holds great promise in addressing the pressing issue of heavy metal contamination in the environment.

The economic implications of utilizing *Cyperus rotundus* as a phytoremediation agent present a complex picture. While the inherent low-cost nature of plant-based remediation is attractive, particularly compared to traditional engineering solutions, several factors must be considered. The widespread availability of *C. rotundus* reduces initial procurement costs, and its natural resilience minimizes the need for intensive maintenance or specialized inputs. However, the economic feasibility of large-scale implementation hinges on the value of the recovered metals and the efficiency of the harvesting and processing stages. If *C. rotundus* is used as a hyperaccumulator, the recovery of valuable metals like tin could offset operational costs and potentially generate revenue. Conversely, if it is used primarily for phytostabilization, the economic benefit lies in the prevention of costly environmental damage and the potential restoration of land for other uses. Moreover, the use of microorganisms to enhance contaminant uptake further lowers costs by eliminating the need for intensive chemical processes. The feasibility of large-scale implementation also depends on the development of efficient harvesting techniques, the establishment of processing facilities for metal extraction or biomass disposal, and the integration of phytoremediation into broader land management strategies. Despite these challenges, the long-term economic benefits, including reduced remediation costs, improved soil quality, and the potential for reusing land for agriculture or other purposes, make microorganism-assisted phytoremediation a viable and sustainable solution for tackling contamination, particularly in resource-limited settings. Further research is needed to quantify the long-term economic benefits and to develop cost-effective strategies for scaling up this approach.

CONCLUSIONS

The potential of *Cyperus rotundus* L. as a hyperaccumulator of heavy metals, such as Mn, As, Cd, Cu, Ni, Fe, and Pb, is confirmed by this review. High metal concentrations, however, may prevent it from growing and lower the effectiveness of cleanup. Arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) work together to improve metal absorption, stress tolerance, and overall phytoremediation efficacy. Even though *C. rotundus* works well on its own, microbial symbiosis greatly increases its remedial capacity. To maximize plant-microbe interactions and environmental conditions for large-scale applications, more study is required. This method provides a sustainable and economical way to handle heavy metal pollution. However, this study has some limitations, including a limited number of studies and the potential bias in the selection of studies. Further research is required to fully comprehend the complexities of these plant-microbe interactions and optimize the use of this technology for large-scale environmental remediation.

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