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Editorial

Advancements in Phytoremediation Research for Soil and Water Resources: Harnessing Plant Power for Environmental Cleanup

Jae K. Park [1,*] and Kokyo Oh [2]

[1] College of Engineering, University of Wisconsin-Madison, Madison, WI 53706, USA
[2] Center for Environmental Science in Saitama, Kazo City 347-0115, Saitama, Japan; o.kokyo@pref.saitama.lg.jp
* Correspondence: jkpark@wisc.edu

Phytoremediation, an environmentally conscious and sustainable strategy, revolves around harnessing the power of plants to counteract the harmful impacts of pollutants on our ecosystems. This innovative approach capitalizes on plants' innate capabilities to absorb and detoxify pollutants and accumulate them, effectively detoxifying soil, water, and air. Over the last decades, phytoremediation has garnered remarkable recognition for its potential to combat a spectrum of environmental woes, ranging from the scourge of heavy metal contamination to the insidious presence of organic pollutants and even the challenge posed by radioactive elements. Recently, the forefront of phytoremediation has witnessed groundbreaking progress, marked by the emergence of novel techniques, the realm of plant genetic engineering, and a heightened comprehension of the intricate interactions between plants and microbes.

Central to this compilation is the resounding call for effective technologies dedicated to soil and water conservation and remediation. The introduction magnifies the urgency of global soil and water contamination, advocating for developing technologies capable of preserving these invaluable resources and reinstating their vitality.

Within this context, phytoremediation emerges as an eco-friendly and cost-effective approach to combat contamination. While initially focused on removing hazardous contaminants from soil and groundwater, its scope has now expanded far beyond, embracing diverse domains like resource management, wastewater treatment, and the safeguarding of ecosystems. This transformation speaks volumes about its adaptable potential to address environmental challenges. Therefore, this editorial aims to summarize the Special Issue "Phytoremediation Technologies for Soil and Water Resources Conservation".

Yu and He explore the untapped potential of tea saponins, exploring their role in enhancing the phytoremediation of cadmium-contaminated soil. This innovative exploration quantifies the positive impact of tea saponins, optimizing their application parameters and paving a promising path for practical field remediation. The findings underscore the viability of harnessing natural compounds to bolster the effectiveness of phytoremediation.

Venturing deeper into the intricate dance between plants and soil, Wang et al. probe the response of castor seedling roots to the combined onslaught of cadmium and zinc pollution. The research unveils the intricate interplay of these heavy metals, influencing root morphology, nutrient dispersion, and enzyme activities. This illumination enriches our comprehension of the mechanisms that govern plant adaptation in contaminated environments.

Stepping beyond laboratories to real-world scenarios, He et al. introduce enhancements to the electrokinetic-permeable reaction barrier (EK-PRB) technology for remediating lead-contaminated soil. This novel approach leverages thin-film PRB materials and microbial augmentation to amplify the technique's efficiency. This innovation surmounts practical constraints by curbing energy consumption and the risk of secondary pollution, potentially broadening the horizons of EK-PRB technology application.

Liu et al. widen its gaze to encompass compost phytotoxicity assessment. Recognizing the pivotal role of non-phytotoxic compost in sustainable agriculture, this research introduces a seedling establishment test as a dependable gauge of compost maturity. This

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innovation presents a tangible solution for appraising compost quality and bolstering soil conservation and crop cultivation.

Dean et al. transport us to aquatic ecosystems, spotlighting aquatic macrophytes as potential allies in combating phosphorus-induced eutrophication. The research validates the potency of these plants in mitigating water pollution through efficient phosphorus removal. Amid escalating concerns over water quality, the potential of these natural water purifiers glimmers with the promise of rejuvenating aquatic habitats.

Luo et al. focus on assessing the maturity of composted livestock manures, considering the phytotoxic effects of immature compost. The commonly used seed germination test for maturity evaluation lacks a formal model. The researchers introduced a time-to-event model to analyze the germination proportion over time in cow dung compost at various composting durations. The model effectively described the germination patterns of Chinese cabbage and garden cress. Notably, immature compost led to delayed seed germination, particularly during the early composting stages. The parameter t50 (half germination time) negatively correlated with radicle length (RL), highlighting a connection between germination and radicle elongation. This study emphasizes that delayed germination due to immature compost can impede seed radicle growth.

Li et al. confronts the pressing challenge of heavy metal contamination risks in vegetables fertilized with organic waste. The investigation unravels the environmental implications of agricultural practices, raising a cautionary flag against the relentless application of organic waste due to the potential bioaccumulation of toxic metals in crops. This study champions prudent waste management strategies in agriculture by uncovering the intricate nexus between organic waste and heavy metal concentrations.

In summary, this editorial review underscores the paramount role of phytoremediation as a potent instrument in rehabilitating contaminated soil and water resources. The studies spotlighted herein contribute to the ongoing evolution of phytoremediation and emphasize this field's interdisciplinary essence. This goes beyond traditional boundaries, addressing an array of environmental concerns. Cumulatively, the research outlined in these papers propels humanity toward a more sustainable future where collaboration with nature becomes the cornerstone of healing our planet's wounds.

These advancements have ushered in an era of enhanced effectiveness and expanded applicability for the following eight phytoremediation strategies.

1. Enhanced Hyperaccumulation of Heavy Metals [1,2]

Hyperaccumulator plants are naturally gifted with the ability to absorb and accumulate high concentrations of heavy metals in their tissues without harm. This makes them ideal for phytoremediation, as they can be used to remove heavy metals from contaminated soil and water.

Researchers have discovered and enhanced hyperaccumulator plants using methods like genetic engineering, selective breeding, and tissue culture. This improves their metal-absorbing abilities, enhancing phytoremediation's effectiveness for heavy metal cleanup. However, hyperaccumulators are not a universal solution, and are only applicable to specific soils and waters. Their use may even pose environmental risks, like introducing heavy metals into the food chain.

2. Phytoremediation of Organic Pollutants [3]

In addition to heavy metals, phytoremediation can also remove organic pollutants from the environment. Organic pollutants include various compounds, such as pesticides, herbicides, and petroleum hydrocarbons. Plants can break down organic contaminants through various mechanisms, including enzymatic degradation, volatilization, and photodegradation. The effectiveness of phytoremediation for organic pollutants depends on several factors, including the type of pollutant, the plant species, and the environmental conditions. Researchers continue to develop new phytoremediation techniques for organic pollutants. One promising approach is to use plant-associated microbes, such as bacteria and fungi, to help degrade the contaminants.

3. Genetic Engineering for Improved Phytoremediation [4]

Genetic engineering enhances phytoremediation. It creates plants more resilient to pollutants, with better accumulation and degradation abilities. One instance is the Indian mustard, engineered to tolerate lead and clean contaminated soil. Although promising, genetic engineering raises ethical concerns due to modified organisms.

4. Nanotechnology and Phytoremediation [5]

Nanotechnology is a rapidly developing field that has the potential to revolutionize phytoremediation. Nanoparticles are tiny particles that have unique properties that can be used to improve the phytoremediation process. For example, nanoparticles can bind to pollutants, making them easier for plants to absorb. Nanoparticles can also deliver pollutants to specific parts of the plant, such as the roots or leaves. The use of nanotechnology in phytoremediation is still in its early stages, but it has the potential to make this technology more effective and efficient.

5. Phytoextraction and Resource Recovery [6]

Phytoextraction is a type of phytoremediation that uses plants to extract metals from contaminated soil. The metals are then harvested from the plant biomass and can be reused or recycled. Phytoextraction is a promising technology for removing heavy metals from the environment. However, it is essential to note that this technique is only sometimes feasible, as it can be expensive and time-consuming.

6. Phytostabilization and Erosion Control [7]

Phytostabilization is a type of phytoremediation that uses plants to stabilize contaminated soil. This prevents the pollutants from leaching into groundwater or being released into the air. Phytostabilization is a cost-effective and sustainable way to manage contaminated soil. This technique is often used with other phytoremediation techniques, such as phytoextraction.

7. Integrating Artificial Intelligence and Monitoring

Artificial intelligence (AI) and remote sensing technologies are being used to improve the monitoring and management of phytoremediation projects. AI algorithms can be used to analyze complex environmental data to optimize plant selection, predict growth patterns, and assess the progress of pollutant removal. Remote sensing technologies like drones and satellites can monitor large-scale phytoremediation efforts in real time. This information can be used to optimize the phytoremediation process and ensure its success.

8. Phytoremediation in Urban Environments [8]

Phytoremediation can also be used to clean up pollution in urban environments. Green roofs, vertical gardens, and constructed wetlands are all examples of phytoremediation techniques that can be used in urban areas.

Phytoremediation presents a versatile array of mechanisms that harness the distinct capacities of plants to uptake, amass, stabilize, disintegrate, and release pollutants found within soil, sludge, and water. These mechanisms and their suitable applications are as follows: [9,10]

- Phytoextraction: This mechanism involves the absorption and subsequent accumulation of detrimental metals, radioactive components, and other pollutants within the biomass of plants. As plants flourish, they adeptly uptake pollutants from their surroundings into their tissues, effectively lowering contaminant concentrations within the soil. The most effective phytoextraction plants can accumulate high concentrations of metals in their tissues, such as sunflowers, Indian mustard and willow trees.
- Phytovolatilization: This mechanism involves the process of vaporization and the subsequent release of volatile organic compounds and vaporized metals like mercury (Hg) and selenium (Se) by plants. Through this removal path, plants actively

expel contaminants in a gaseous state, contributing to their elimination from the environment. Phytovolatilization demonstrates efficacy in addressing pollutants within groundwater and surface water systems. The most effective phytovolatilization plants can release pollutants into the atmosphere at a high rate, such as poplar trees, willow trees, sunflowers, Indian mustard, and Thlaspi caerulescens.

- Phytostabilization: This mechanism involves the interaction of plants with environmental pollutants, resulting in the adsorption, precipitation, and stabilization of both inorganic and organic contaminants. By immobilizing pollutants, plants play a pivotal role in curtailing their further dispersal and subsequent impact on ecosystems. The most effective phytostabilization plants are those that can bind contaminants to their roots or leaves, or that can change the chemical properties of pollutants so that they are less mobile, such as Indian mustard, vetiver grass, poplar trees, willows, and sunflowers.
- Phytostimulation: This mechanism involves the decomposition of organic pollutants through the activation and proliferation of microorganisms in the rhizosphere—the soil region directly influenced by the plant's root system. By facilitating microbial activity, plants contribute to the breakdown of pollutants into less harmful components. The most effective phytostimulation plants can release chemicals that attract microorganisms or provide them with nutrients, such as comfrey, wormwood, sunflowers, legumes, and grasses.
- Phytotransformation: This mechanism involves decomposing, transforming, and detoxifying organic pollutants. Plants modify pollutants into safer forms through biochemical processes, reducing their harmful potential. This mechanism is particularly effective for removing pesticides and other organic contaminants from the soil. The most effective phytotransformation plants can break down pollutants through various biochemical processes, such as poplar trees, sunflowers, Indian mustard, Thlaspi caerulescenes, and Phalaris arundinacea.
- Phytofiltration: This mechanism involves the active adsorption and absorption of pollutants by the root systems of plants. By physically interacting with contaminants, plants serve as natural filters, removing pollutants from the soil and water. This mechanism is particularly effective for removing contaminants from groundwater and surface water. The most effective phytofiltration plants can absorb pollutants at a high rate, such as cattails, water hyacinth, vetiver grass, Phragmites australis (common reed), and Spartina alterniflora.

In recent years, phytoremediation has experienced remarkable progress, expanding beyond its conventional role in toxic contaminant removal from soil and groundwater. This expansion has led to the development of novel strategies and applications that address a spectrum of environmental challenges, transforming phytoremediation into a comprehensive solution. Some of the most significant advancements in phytoremediation are as follows:

- Biodiversity conservation and global warming mitigation: The depletion of biodiversity and the alarming progression of global warming have spurred the exploration of phytoremediation's potential contributions. Researchers have deployed phytoremediation to restore polluted environments and sequester carbon, effectively contributing to climate change mitigation. These efforts address local health and economic development and establish a synergy between pollution control and environmental conservation.
- Elucidation of purification mechanisms and gene technology: The rapid advancements in science and technology have enabled a deeper understanding of how plants interact with pollutants. This includes elucidating absorption pathways, detoxification mechanisms, and the role of microorganisms in phytoremediation. Researchers have leveraged this knowledge to identify genes associated with high absorptive capacity, enhancing the effectiveness of phytoremediation by developing genetically modified plants. Genome editing techniques have allowed the creation of plant species and endophytic bacteria optimized for pollutant removal.

- Phytoremediation and restoration mechanisms: The core of phytoremediation's success lies in its restoration mechanisms. By harnessing phytoextraction, phytovolatilization, phytostabilization, phytostimulation, phytotransformation, and phytofiltration, this technology presents a comprehensive toolkit for addressing diverse contaminants. The intricate interplay between plants, microbes, and soil chemistry drives the efficient removal and containment of pollutants, offering a multi-faceted solution to environmental challenges.
- Phytoremediation in wastewater treatment: Beyond soil and groundwater remediation, phytoremediation has made significant strides in wastewater treatment. Aquatic plants are pivotal in purifying water bodies like rivers, lakes, streams, and ponds. Through rhizofiltration, plants effectively capture and filter contaminants from the water, restoring aquatic ecosystems and enhancing water quality.
- Phytoremediation in biomass and bioenergy production: Phytoremediation with biomass and bioenergy production offers a dual-purpose solution. Resource plants cultivated for phytoremediation can be repurposed as bioenergy crops, providing a sustainable renewable energy source. This integration addresses pollution while simultaneously contributing to the energy transition.
- Profitable phytoremediation: Traditional phytoremediation approaches often overlooked the economic potential of the remediated land post-harvest. Recent advancements have sought to bridge this gap by focusing on ornamental flowers and resource plants (such as sunflowers and corn), which possess high biomass and are amenable to commercial uses. Researchers have successfully transformed contaminated soils into productive sites by cultivating such plants, generating revenue through flower production and biofuel cultivation.
- Urban phytoremediation: Urban environments, marked by concrete landscapes and industrial activities, face unique pollution challenges. Phytoremediation has emerged as a tool to transform urban spaces into cleaner and healthier environments. Green roofs, vertical gardens, and constructed wetlands adorned with diverse plants facilitate pollutant removal, improve air quality, and contribute to urban aesthetics.

These are just some of the advancements made in phytoremediation in recent years. As research in this area continues, we will likely see even more innovative and practical applications of this promising technology in the future.

Despite its numerous merits, phytoremediation has its challenges. The technology's efficiency can be influenced by factors such as plant selection, soil conditions, and contaminant types. Moreover, the timescale required for complete remediation may need to align with urgent pollution problems. Researchers are actively exploring ways to enhance phytoremediation's effectiveness, including using engineered plants, microbe-assisted remediation, and optimizing growth conditions.

Other challenges to the widespread adoption of phytoremediation include regulatory frameworks and public acceptance. Developing guidelines and standards for phytoremediation and public education initiatives can foster a more favorable environment for the technology's implementation.

Despite these challenges, phytoremediation has the potential to be a significant tool for environmental cleanup in the future. Continued research and development are needed to address phytoremediation's challenges and make it more efficient and effective. However, the potential benefits of phytoremediation are significant. It is a natural, sustainable, and cost-effective way to clean up contaminated sites. It can be used to remove various pollutants, including heavy metals, organic pollutants, and radioactive contaminants, and it has the potential to be used on a large scale to address the global problem of environmental pollution.

Phytoremediation is a promising technology with the potential to make a significant contribution to environmental cleanup. Continued research and development are needed to address the challenges of phytoremediation and to make phytoremediation more efficient and effective. However, the potential benefits of phytoremediation are significant. It is a natural, cost-effective, and environmentally friendly way to clean up contaminated sites. It can be used to remove various pollutants, including heavy metals, organic pollutants, and radioactive contaminants. And it has the potential to be used on a large scale to address the global problem of environmental pollution.

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