Phytotechnology as green infrastructure: a nature-based approach for environmental problems in Welang river basin, East Java

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Abstract. This study aimed to review the concepts, mechanisms, applications, and future directions of phytotechnology—particularly phytoremediation—as a nature-based solution for river basin restoration, with a focus on the Welang River Basin in East Java, Indonesia. A literature-based review was conducted using nine key studies, including local field assessments of riparian vegetation and water quality. The review explored components of phytotechnology such as phytoremediation, phytofiltration, phytomonitoring, and phytostructure. Case studies from Poland, India, and Indonesia showed successful applications in addressing heavy metal and organic pollution. In the Welang Basin, species richness decreased downstream, correlating with increased pollutant levels, indicating the relevance of native phytoremediators. Advantages include low cost, ecosystem benefits, and public acceptance, while limitations involve slow remediation rates, pollutant tolerance issues, and site specificity. Phytotechnology offers a sustainable, low-impact alternative for improving river health and ecological function. Its integration into watershed management aligns with conservation goals and supports the achievement of Sustainable Development Goals (SDGs). This review highlights its potential for broader application in tropical river systems and contributes to advancing green infrastructure approaches in environmental management.

1 Introduction

Rivers are vital freshwater resources that support biodiversity and human needs. In Java, Indonesia, rapid urban growth, agricultural intensification, and poor land management have accelerated river ecosystem degradation [1]. The Welang River Basin, flowing through Malang Regency, Pasuruan Regency, and Pasuruan City, exemplifies this crisis. With a

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catchment area of 511.6 km², a main river length of 40.09 km, and support from 57 tributaries and 79 springs, its strategic location links mountainous conservation zones with urban areas [2]. However, increasing pollution, erosion, and vegetation loss have severely impacted the river's ecological function [3]. Restoring such a complex landscape requires nature-based and cost-effective solutions.

Phytotechnology is an emerging nature-based approach that uses plants, especially riparian vegetation, to stabilize riverbanks, improve water quality, and provide ecosystem services [4]. Riparian zones form natural buffers between aquatic and terrestrial ecosystems and are essential for trapping sediment, filtering nutrients, absorbing pollutants, and sustaining habitat[1;5]. Unfortunately, these vegetated corridors are increasingly fragmented by land conversion, deforestation, and infrastructure. Research in the Welang Basin shows that areas with reduced riparian vegetation tend to have lower water quality and limited ecological resilience [6]. River-dependent communities contribute to this pressure through activities that introduce wastewater, agricultural runoff, and heavy metals into the system [7]. Therefore, restoring riparian zones with native plants offers both ecological and social benefits.

Phytoremediation, a core component of phytotechnology, involves using plants to extract, stabilize, or degrade pollutants in soil and water. It is widely considered a low-cost, environmentally friendly, and sustainable alternative to conventional treatment technologies [2;8]. Mechanisms such as phytoextraction, rhizofiltration, and phytostabilization enable specific plants to address various contaminants depending on site conditions [9]. In the Welang River Basin, species from families like Fabaceae, Moraceae, and Meliaceae dominate riparian zones and show resilience in polluted habitats [10]. Vegetation surveys reveal a gradient of biodiversity: 171 species upstream, 67 in the midstream, and 37 downstream, correlating with declining environmental quality [2;11]. These findings support targeted replanting and rehabilitation using native species with known phytoremediation potential.

The effectiveness of phytoremediation is influenced by multiple abiotic and biotic factors. Water chemistry, such as pH, TDS, and metal concentrations, significantly affects plant uptake capacity and pollutant transformation [7]. Environmental parameters including light intensity, humidity, and temperature also influence plant performance in riparian zones [12]. In upstream areas, lower pollutant concentrations are associated with richer species diversity, while downstream locations exhibit higher Pb, Cu, and fluoride levels alongside vegetation decline [3]. Conservation zones such as the Purwodadi Botanic Garden and Baung Nature Park serve as reservoirs for in- situ and ex-situ plant diversity, providing important resources for restoration initiatives [2]. Strategic use of these areas can accelerate plant propagation, monitoring, and public awareness.

Integrating phytotechnology into watershed management provides multiple long-term benefits beyond remediation. Research suggests that pairing riparian vegetation restoration with sediment traps, community- managed wetlands, and flood buffer strategies can increase resilience and cost-efficiency[3]. These approaches align with international frameworks like the Global Strategy for Plant Conservation (GSPC) and support the goals of SDG 6 (Clean Water), SDG 13 (Climate Action), and SDG 15 (Life on Land) [2]. However, phytotechnology remains underutilized due to limited awareness, weak policy integration, and insufficient investment in plant-based research. Local governments and stakeholders must collaborate to embed phytotechnology into river basin governance. Doing so can promote both ecological restoration and sustainable development in vulnerable tropical watersheds.

This review synthesizes current knowledge on phytotechnology and phytoremediation in the Welang River Basin, drawing from upstream to downstream research. It explores definitions, mechanisms, field applications, and influencing factors while highlighting strengths and challenges of this approach. By examining the basin as a model, the review also offers broader implications for river rehabilitation across Southeast Asia. Emphasizing native biodiversity, community participation, and strategic conservation, the paper argues for mainstreaming phytotechnology as green infrastructure. Future river management must shift from reactive pollution control to proactive, ecosystem-based planning rooted in nature-based solutions. The Welang River, with its ecological complexity and documented degradation, serves as a relevant and urgent case study.

2 Research methods

2.1 Research Type

This study employs a literature-based review approach, focusing on the synthesis of concepts, mechanisms, and applications of phytotechnology and its relevance to the Welang River Basin. The analysis is supported by nine key studies supplemented with additional scientific literature.

2.2 Data Sources

The review uses secondary data, including:

a. National and international scientific articles addressing the concepts and mechanisms of phytotechnology;
b. Local research conducted in the Welang River Basin, particularly studies on riparian vegetation and water quality;
c. Case studies on the implementation of phytotechnologies in other countries such as Poland, India, and Indonesia

2.3 Literature Collection Procedure

The literature collection process involved:

a. Topic identification, including phytotechnology, phytoremediation, riparian vegetation, and environmental conditions of the Welang Basin;
b. Systematic literature searches across journals, conference proceedings, and research reports;
c. Selection of key studies, focusing on nine highly relevant and comprehensive references;
d. Information extraction, covering conceptual frameworks, phytotechnology mechanisms, vegetation composition, pollutant data, and practical application examples

2.4 Data Analysis

Data were analyzed using a descriptive–analytical approach that combined comparative, integrative, and conceptual assessments. The analysis compared upstream–midstream–downstream conditions with global studies, linked riparian vegetation decline to rising pollutant levels and species suitability for phytotechnology, and clarified key plant mechanisms such as apoplastic/symplastic transport, chelation, and detoxification. The advantages and limitations of phytotechnology were also evaluated based on the reviewed literature.

3 Results and discussion

3.1 Integrating phytotechnology and phytoremediation: concepts and scope

Phytotechnology is a science-based, environmentally friendly approach that applies plant systems to address environmental challenges such as pollution, land degradation, and ecosystem instability. Defined as the application of plant science and engineering for environmental problem- solving, phytotechnology harnesses the biological capabilities of plants to remediate soil and water contaminated by heavy metals, organic pollutants, or nutrients [13;14;15]. This method offers a low-cost, sustainable, and aesthetically integrated solution to many environmental issues that conventional chemical or mechanical methods struggle to address. In river systems such as the Welang Basin, where pollution levels are rising due to urban and agricultural pressures, phytotechnology presents a promising strategy for ecological restoration. The approach also aligns with global goals for nature-based solutions, supporting biodiversity conservation while improving water quality.

One of the most widely applied branches of phytotechnology is phytoremediation, which refers to the use of plants to remove, detoxify, or stabilize environmental contaminants. This technique is particularly effective for treating heavy metal pollution, which is a major issue in many tropical rivers. Multiple methods exist under the phytoremediation umbrella: phytoextraction, where plants absorb contaminants and store them in aboveground tissues; phytostabilization, which involves immobilizing pollutants in the soil to prevent leaching [16]; and phytodegradation, in which plants metabolically transform organic pollutants into less toxic forms [17]. Additionally, phytovolatilization enables certain species to absorb pollutants and release them into the air in a less harmful form [17], while phytofiltration allows for root-based removal of pollutants from water [16;18]. These techniques have been demonstrated in various tropical watersheds, including in Welang's middle and downstream zones, where riparian vegetation like Avicennia marina and Albizia spp. show potential for metal uptake and sediment stabilization [10].

Another important yet underutilized tool is phytomonitoring, which involves using plants as bioindicators to detect environmental contamination. Vegetation found in botanic gardens or natural riparian corridors can reflect the quality of air, soil, or water, depending on pollutant accumulation in their tissues [19]. In the Welang Basin, vegetation assessments have revealed that species diversity declines downstream, mirroring increased pollutant loads of lead (Pb), copper (Cu), and TDS in water bodies. This makes phytomonitoring a valuable tool for long-term ecological surveillance and environmental planning.

Phytostructure, another component of phytotechnology, focuses on using plant-based systems as physical infrastructure to stabilize riverbanks, reduce erosion, and restore habitats. In areas with steep slopes or degraded soils, strategically planted vegetation acts as living structures that reduce runoff and enhance soil cohesion. In the upstream sections of the Welang River, where slope instability and deforestation are prominent, this method has been proposed as a tool to minimize sediment flow into the watershed. Beyond erosion control, phytostructures contribute to ecosystem resilience, providing microhabitats for riparian fauna and improving aesthetic landscape values [13].

Overall, the components of phytotechnology—phytoremediation, phytomonitoring, phytofiltration, and phytostructure—function in an integrated manner to restore ecological balance in polluted landscapes. When applied to river systems like Welang, these plant-based strategies not only treat contamination but also reinforce the hydrological and biological integrity of the watershed. The next section will explore how these methods have been applied practically in the Welang River Basin, using site-specific data to illustrate their potential for watershed-scale restoration.

3.2 Practical applications in watershed management: case of the Welang River

Phytotechnology has emerged as a practical tool for sustainable river basin management, combining ecological knowledge with engineering principles to reduce pollution and rehabilitate degraded waterways. Its application in watershed systems supports the removal of heavy metals, excess nutrients, and organic pollutants through the use of plants and constructed ecological features. Both international and Indonesian case studies demonstrate the effectiveness of phytotechnology in improving water quality, stabilizing riparian zones, and enhancing ecosystem services. In tropical countries like Indonesia, where conventional wastewater infrastructure may be lacking or overburdened, phytotechnology offers a low-cost, scalable, and environmentally harmonious solution.

A landmark application of phytotechnology was implemented in the Pilica River catchment, Poland, where a combination of ecohydrology and phytotechnology was used to combat nutrient pollution and toxic algal blooms. According to [20], this approach improved water quality, reduced eutrophication, and even enabled renewable bioenergy production from harvested plant biomass. These multifunctional outcomes demonstrate how phytotechnology can bridge ecological health and sustainable development in river basins.

In a more species-specific approach, Salvinia molesta was evaluated in a moderately polluted river for its ability to improve water chemistry. [21] also found that the aquatic fern enhanced dissolved oxygen by 58%, while reducing total solids (31%), TDS (97%), BOD (26%), and COD (74%). This study affirms the species' strong phytoremediation potential for organic pollutant removal, especially in lowland rivers impacted by household and agricultural waste.

Technological innovation has also been integrated with phytotechnology, as shown in the Yamuna River, India. [22] combined phytoremediation with AI-assisted monitoring and prediction models to optimize the removal of heavy metals, offering a smart, adaptive framework for large-scale applications. Such approaches could be highly relevant for urban watersheds in Java, where pollution levels are dynamic and multi-sourced.

In Indonesia, phytoremediation has been explored using native mangrove species in estuarine environments [23], demonstrated that Acanthus ilicifolius effectively accumulated copper (Cu) in its roots and shoots, supporting its use for phytostabilization in the Jagir River estuary near Surabaya. This application parallels the situation in the downstream Welang River, where [2] documented the presence of metal-tolerant riparian species despite elevated Pb and Cu levels.

In the upstream and midstream Welang [5;7] identified areas with rich riparian vegetation (e.g., Ficus, Albizia, and Bambusa species) that could serve as natural filters and slope stabilizers. However, vegetation density and species richness decline sharply in urbanized zones, coinciding with increased TDS and metal contamination [6;7]. This gradient reveals clear opportunities for targeted phytostructure and wastewater garden design along pollution corridors.

Globally, phytotechnology has also been used for industrial effluent treatment, greywater recycling, and sediment stabilization, producing useful biomass in the process. [24] notes that such systems reduce environmental toxicity while generating resources like mulch, compost, and biogas. For the Welang River Basin, where land availability and biodiversity remain, these methods could be integrated with community-based water management to support conservation and local livelihoods.

These case studies—ranging from Europe to India and East Java— demonstrate the adaptability and cost-effectiveness of phytotechnology for improving water quality and strengthening ecosystem resilience. With support from local science, phytotechnology can move from pilot projects to mainstream infrastructure in Indonesian watersheds.

3.3 Functional mechanisms of phytoremediation

Basically, plants have several mechanisms for the uptake and translocation of heavy metals. The uptake of heavy metals into roots occurs through two pathways: the apoplastic pathway (passive diffusion) and the symplastic pathway (active transport against electrochemical potential gradients and concentration across the plasma membrane) [25]. The symplastic pathway is an energy-dependent process mediated by metal ion carriers or complexing agents. For example, Cd accumulated preferentially in the apoplast. In the symplast, O ligands increased with increasing Cd concentrations; in the apoplast, sulphur-based (S)-ligands prevailed [26]. Meanwhile Cu and Zn entering in the root of plant using apoplast mechanism [27].

Refer to [25], plants have two defense strategies to cope with the toxicity of heavy metals: avoidance and tolerance. The avoidance strategy limits the uptake and movement of heavy metals into plant tissues. Plants can immobilize heavy metals through root sorption or by modifying metal ions using root exudates such as organic acids and amino acids. These exudates can change the pH of the rhizosphere, leading to the precipitation of heavy metals and reducing their bioavailability. Metal exclusion mechanisms also exist between the root system and shoot system to protect aerial parts against harmful heavy metals. Furthermore, the tolerance strategy is the second line of defense at the intracellular level

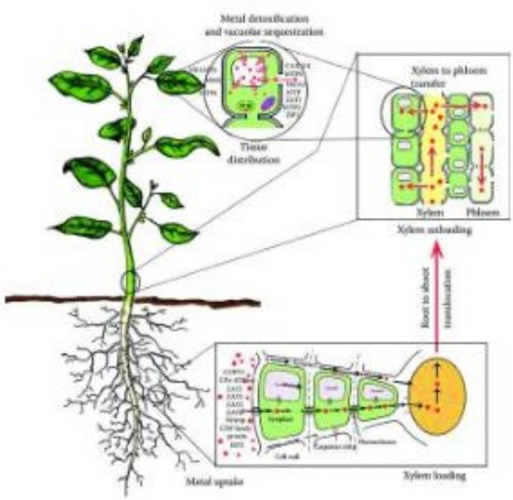

Figure 1. Mechanisms of heavy metal transport and accumulation in plants [28]

Therefore, the mechanism of plants when uptake heavy metals (including Sansevieria) were:

a. Presence of Heavy Metals in the Environment: Heavy metals exist in the soil in insoluble forms, which are not readily available to plants. They originate from natural or anthropogenic sources such as industrial activities, agriculture, sewage sludge, mining, and pesticide application.

b. Bioavailability of HMs: Plants release root exudates that can change the pH of the rhizosphere and increase the solubility and bioavailability of heavy metals [29]. Root exudates play a crucial role in altering the bioavailability of metals. The release of specific organic compounds serves not only to mobilize metals by creating metal complexes but also acts as a source of nutrients and energy for microbial communities. Root exudates consist of organic acids, amino acids, and phytochelatins (PC), functioning as binding compounds within plant cells for heavy metals [30].
c. Root Uptake: Plants take up heavy metals through two pathways: apoplastic pathway (passive diffusion) and symplastic pathway (active transport against electrochemical potential gradients) (See Figure 2). In the apoplast pathway, heavy metals are transported through the intercellular spaces and the space between the cell wall and the plasma membrane [31]. On the other hand, the symplast pathway involves the transport of heavy metals into the cell through transporters and then between cells through plasmodesmata. While the symplast pathway involves active transport against electrochemical potential gradients and concentration across the plasma membrane [30].

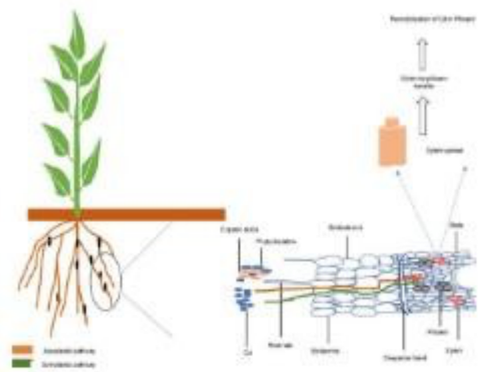

Figure 2. Pathways for Heavy metals uptake in Plants [32].

d. Chelation and Detoxitications: Once heavy metals enter the roots of plants (cytosol), they can be chelated and transported to the vacuole for storage [25]. Chelation is the process by which heavy metals are bound to organic molecules, such as amino acids, peptides, and organic acids, to form complexes that are more stable and less toxic to the plant [33]. The chelation process is mediated by metal-binding proteins which are involved in the detoxification and sequestration of heavy metals in plants. The organic compounds involved in heavy metal ion chelation include organic acids, amino acids, phytochelatins (PCs), metallothioneins (MTs), and cell wall proteins/pectins/polyphenols [34]. Organic acids within cells prevent the persistence of heavy metals as free ions in the cytoplasm by complexing and reducing their bioavailability to plants [25].

Once chelated, heavy metals can be transported to the vacuole, where they are safely stored and prevented from interacting with other cellular components [35]. The transport of heavy metals to the vacuole involves the symplastic pathway, where heavy metals are transported through the cytoplasm and across the tonoplast membrane into the vacuole. This process is mediated by transporters, such as the tonoplast-localized heavy metal ATPases, which are involved in the sequestration of heavy metals in the vacuole [36]

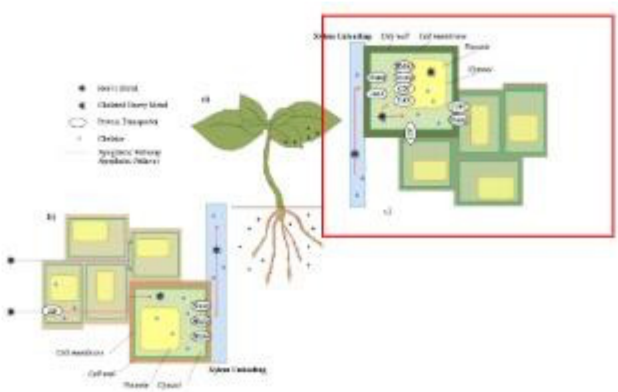

Figure 3. Chelation and detoxification mechanism [36].

e. Translocation and Sequestration: Heavy metal ions sequestered inside vacuoles can be transported into the stele and enter the xylem stream via the root symplasm. They are then translocated to the shoots through xylem vessels. In leaves, the ions are sequestered in extracellular compartments or plant vacuoles, preventing accumulation of free metal ions in the cytosol [25].

Stored of Heavy Metals: In addition to vacuoles, heavy metal ions can be stored and separated in alternative sites, including leaf petioles, leaf sheaths, and trichomes [25]. These locations are less susceptible to damage from heavy metals. Furthermore, heavy metals can be transported to aging leaves and expelled from the plant through the natural shedding of leaves [34].

3.4 Advantages, limitations, and future directions of phytotechnology

Phytotechnology, especially phytoremediation, presents several advantages as an environmentally friendly and cost-effective strategy for pollution control. It is widely recognized as a low-cost, sustainable, and less intrusive method for remediating contaminated environments by using plants to degrade, transform, or stabilize pollutants [37;38;39]. Its eco-friendly nature makes it suitable for areas where minimal environmental disruption is preferred. Moreover, phytotechnology is versatile, applicable across various environments such as soil, water, and air, and capable of treating a wide array of contaminants including heavy metals, organic pollutants, and radionuclides [40;38;39]. The approach also offers additional ecosystem benefits, such as erosion control, improved soil quality, carbon sequestration, and enhanced habitat for wildlife [40;41;13]. Furthermore, due to its green and aesthetic form, phytotechnology enjoys broad public acceptance and is compatible with urban design and landscape planning [37;42].

In addition to ecological and social benefits, phytotechnology also contributes to economic opportunities. Biomass generated during phytoremediation processes can be repurposed into bioenergy, biofuels, and other valuable materials, adding an economic dimension to its environmental advantages [40;43]. This dual functionality increases its potential for integration into circular economy frameworks. However, the adoption of phytotechnology is not without limitations. One significant drawback is its slow remediation pace; the process often requires extended periods to reach desirable levels of pollutant reduction, especially compared to traditional methods [42;15]. The effectiveness of phytoremediation also depends on the plant species' ability to tolerate and absorb high concentrations of contaminants, which may be a limiting factor in severely polluted areas.

Another challenge lies in the site-specific nature of phytotechnology. Its success varies significantly depending on environmental conditions and the types of pollutants present, necessitating local field trials before implementation [15]. Regulatory and technical challenges further complicate its deployment. For instance, there is still a need for deeper understanding of plant-microbe interactions and pollutant detoxification mechanisms to optimize performance [44;15]. Despite these limitations, several promising directions are being pursued to enhance phytotechnology's effectiveness. One focus is the use of plant-associated microbes to support pollutant breakdown and improve plant health in contaminated conditions [45;38]. Genetic engineering, including the application of omics technologies, is also being explored to develop plant varieties with superior contaminant uptake and detoxification capabilities [46;44;14].

Beyond technical improvements, future efforts aim to integrate phytotechnology into public health strategies, emphasizing its role in minimizing environmental exposure to hazardous substances [13]. Commercialization is also a key direction, with emphasis on creating market-driven solutions that generate high-value biomass and related products [47;48]. Lastly, advancing from laboratory-scale research to full field-scale applications is essential, including the development of reliable monitoring tools and performance metrics [49]. In addition, although phytotechnology faces several challenges, its environmental, economic, and public health potential ensures it remains a significant area for future research and application

4 Conclusion

Phytotechnology offers a nature-based, low-cost, and sustainable solution to the growing challenge of environmental pollution in river basins. Through mechanisms such as phytoremediation, phytofiltration, phytomonitoring, and phytostructure, this approach utilizes the natural capabilities of plants to remove, stabilize, or monitor pollutants across various environmental media. Case studies from both global and Indonesian contexts—including the Welang River Basin—demonstrate the practicality of phytotechnology in improving water quality, restoring ecological function, and supporting community-based environmental management. Despite its advantages, such as ecosystem co-benefits and public acceptance, the slow rate of pollutant removal and site-specific limitations remain key challenges to wider adoption. Current research and innovation are focused on addressing these issues through enhanced plant-microbe interactions, genetic engineering, and commercial-scale applications. With continued interdisciplinary collaboration, phytotechnology has the potential to be mainstreamed into river restoration and watershed governance as a resilient, multifunctional green infrastructure solution.

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