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*Review Article*

# Integrated Bio-Ecological Methods for Soil and Water Remediation: A Comprehensive Systematic Review

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## Abstract

Heavy metal and organic pollutants as well as agricultural and industrial contaminants, have caused worldwide soil and water contamination problems that need sustainable treatment approaches. In this review, we investigate bio-ecological remediation technologies with a special focus on the processes, integrated applications, and novel developments. They include phytoremediation, microbial Mycoremediation, Vermiremediation, rhizoremediation, and constructed wetlands, which provide means for contaminant stabilization, degradation, and removal. Transgenic and hyperaccumulator plants have developed phytoremediation techniques such as phytoextraction, Phytostabilization, and phytodegradation. Enzymatic and metabolic flexibility by microbial and fungal systems to break down hydrocarbons, pesticides, and industrial compounds is improved by bioaugmentation or biosorptive techniques. Vermiremediation enhances soil aeration and microbial activity, as do constructed wetlands and rhizosphere-engineered systems for the scalable wastewater treatment and nutrient reclamation. These techniques have been improved in recent years. Combined use of nanoparticles, bio-nano hybrids, genetically modified organisms, and biosensors has created specific and effective remediation networks. Integration of AI and IoT solutions makes it possible to monitor and adjust the remediation conditions in real-time. Although bio-ecological treatments provide several advantages, namely low energy requirement, environmental compatibility, and ecosystem restoration potential, drawbacks such as climate dependence, low rates of degradation, and regulatory issues can be identified. The development of integrated remediation processes using biotechnological and digital tools is a promising opportunity for environmental practices. This review underscores the inter-disciplinary roles of biological, ecological, nanotechnological, and environmental engineering aspects in achieving sustainable remediation of soil and water contaminated with these organisms.

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## 1. INTRODUCTION

Bio-ecological remediation is the use of organisms (plants, microorganisms, fungi, earthworms) and ecological concepts for the treatment of contaminants in soil and water. Taking advantage of life itself to re-establish ecosystems, this strategy combines environmental biotechnology, ecology, and sustainable land management [1]. Since the Industrial Revolution, soil and water contamination have become an area of concern for all parts of the world. Heavy metals, POPs, hydrocarbons, and nutrients are ecosystem contaminants of soil. The waterbodies are subjected to pollution from sewage, agricultural runoff, and industrial effluents [2]. Reports over 80% of wastewater is untreated. The integrated bio-ecological treatment of contaminants through phytoremediation, microbial bioremediation, mycoremediation, and ecohydrological interventions is available. Such integration increases plant efficiency–microbe interactions and stabilizes biocides [3]. Phytoremediation involves hyperaccumulator plants to absorb contaminants and rhizobacteria to enhance contaminant degradation. Many fungi, such as Pleurotus ostreatus, degrade hydrocarbons through mycoremediation [1, 4]. Earthworms enhance soil structure and microbial activity. Integration provides ecologically sound and cost-effective remediation, in particular for developing countries. These practices also regenerate soil fertility and biodiversity. Although integrated strategies are met with difficulties such as long-term remediation and bioaccumulation hazard, improvements made in nanobiotechnology and molecular ecology provide new ways forward.

### 2.4 Advanced Microbes and Biosensors

Monitoring Smart combinations of improved microbes and biosensor monitoring may revolutionise eco-remediation systems [3, 5].

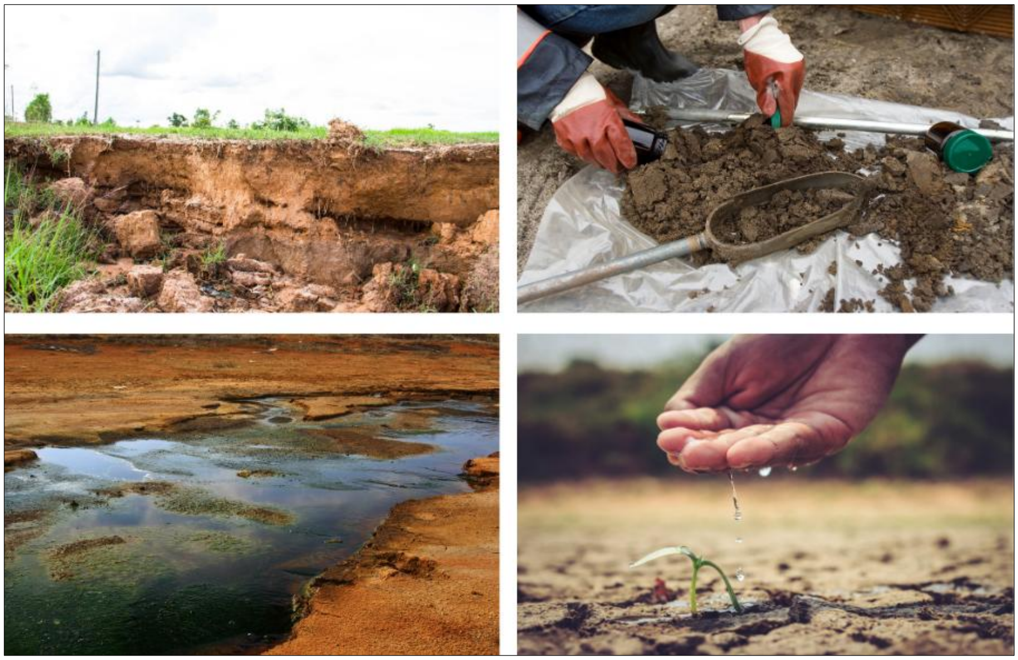

**Figure 1:** Integrated bio-ecological methods for soil and water remediation processes and interactions.

## 2. Overview of Bio-Ecological Remediation Technologies

Bio-ecological remediation technology refers to the use of biological objects or systems to eradicate, fix, or detoxify pollutants from soil and water. These methodologies enhance ecosystem functioning by using natural properties of plants, microbes, fungi and other biotic agents. With increasing anthropogenic pressures, the implementation of these nature-based solutions is becoming increasingly attractive worldwide because of its low cost, eco-friendliness and potential scalability in both rural and industrial environments [6].

### 2.1 Definition and Scope

Bio-ecological Remediation -- The use of living organisms and ecological principles to restore contaminated environments. Fundamental process involve biodegradation, phytoaccumulation, biosorption, and biotransformation, along with the synergistic relations in soil and water niches among other ecologies. Such technologies may be more optimal when applied at the site-specific level and incorporate physical or chemical amendments such as biochar or natural coagulants for better results.

### 2.2 Classification of Bio-Ecological Remediation Technologies

**Phytoremediation**

Phytoremediation, a cost-effective alternative for the remediation of polluted soils and water. It includes processes by which plants take up or detoxify pollutants. It is also potentially possible to phytextract contaminants including heavy metals

such as cadmium, arsenic, and lead, into aboveground biomass [7, 8]. For the former, pollutants are immobile in the rhizosphere and will not spread. Phytodegradation involves organic contaminants and the plant enzymes that break them down into less toxic forms. The phytovolatilization allows plants to take in pollutants and release them as gases through transpiration.
Recent developments aim at improving the plant uptake efficiency and also extending its applicability to compounds of higher complexity. Developments include metal uptake enhancing, plants transformed with transgenes, and species that are metal hyperaccumulators or tolerate high levels of metals. Chelating agents enhance metal solubility for plant assimilation. Utilization of microbial inoculants in the phytoremediation process stimulates the growth and pollutant degradation of plants in the rhizosphere. Together, these approaches integrate plant systems with microbial and chemical tools to enhance expressed function in rehabilitation under field conditions [9].

### Microbial Remediation

This approach employs bacteria, actinomycetes, or archaea for the metabolism or conversion of contaminants. Microorganisms can degrade various organic pollutants such as petroleum hydrocarbons, pesticides, and medicines. Biostimulation (adding nutrients) and bioaugmentation (adding specialized strains) are typical enhancements. A new development is that the bio-treatment can be combined with nanoparticles or biochar as carriers for microbial growth and adsorption of pollutants [10].

### Mycoremediation

Early mycoremediation describes the degradation of organic compounds and the adsorption of heavy metals by fungal biomass, primarily white-rot and brown-rot fungi. Their hyphal and enzymatic systems (for example, laccases and manganese peroxidases) are particularly well adapted to degrade complex pollutants such as dyes, PAHs, and even plastics [11]. Fungal biomass is also being considered as a biosorbent for wastewater treatments for being less expensive and biodegradable.

### Vermiremediation

Earthworm, especially *E. fetida*, is employed for vermicomposting to improve the existing microbial activity and aeration in contaminated soils. The digestion of earthworm converts the chemical form of heavy metals, and their castings are high in beneficial microorganisms. Recent research has also demonstrated that earthworms can contribute to the degradation of microplastics and pharmaceutical residues in combination with organic amendments [12]. Table 1 summarizes the classification of Bio-Ecological Remediation Technologies, their key features, and typical applications.

**Table 1:** Classification of Bio-Ecological Remediation Technologies

| Remediation Method | Key Mechanism | Typical Contaminants | Applications | References |
|---|---|---|---|---|
| Phytoremediation | Uptake, degradation, or stabilization of pollutants via plants | Heavy metals, hydrocarbons, pesticides | Contaminated soil, mine tailings | [13, 14] |
| Microbial Remediation | Biodegradation, the transformation of pollutants using bacteria or consortia | Hydrocarbons, pesticides, industrial waste | Soil, wastewater, and sludge | [10, 15] |
| Mycoremediation | Fungal enzymatic breakdown or adsorption of organic/inorganic pollutants | Dyes, PAHs, heavy metals | Industrial wastewater, soil | [16] |
| Vermiremediation | Earthworm digestion and enhancement of microbial activity and metal bioavailability | Organic waste, heavy metals | Composting, soil detoxification | [12] |
| Constructed Wetlands | Plant–microbe–substrate interaction to filter and degrade pollutants | Nutrients, pathogens, metals | Municipal/agricultural wastewater | [17] |
| Rhizoremediation | Rhizosphere microbes degrade pollutants stimulated by root exudates | Hydrocarbons, nitrogenous compounds | Polluted soil, wetland margins | [18] |

## 3. Phytoremediation Strategies

Phytoremediation employs plants to degrade or neutralize contaminants in soil and water using biological mechanisms. Hyperaccumulator plants contain elevated levels of heavy metals in their biomass, such as Pteris vittata for arsenic, Brassica juncea for lead, and Thlaspi caerulescens for zinc. These have the phytoextraction potential of transferring pollutants into harvestable aerial parts. Other processes include phytostabilisation, in which pollutants are immobilised in the rhizosphere by plants – this occurs especially with lead at mercury. Phytodegradation activates enzymes in various plants, such as Populus or Vetiveria zizanioides, to metabolize organic pollutants. Phytovolatilization volatilizes contaminants to volatile compounds and those are withdrawn through transpiration. In recent years, Pteris vittata has been reported to accomplish 75% of arsenic removal [16], and Vetiver grass has been used to reclaim oil-contaminated soils [17]. Although phytoremediation sounds hopeful, it has some limitations such as slow treatment rates, shallowness of the root system, and possibility of pollutant transfer. Remediation efficiency relies on soil characteristics and the bioavailability of the pollutant. The choice of a suitable plant should take into account the pollutant, the accumulation capacity, and the biomass produced. Application of microbial inoculants can alleviate these limitations [19, 20].

## 4. Microbial and Mycoremediation

Microbial and mycoremediation are parts of bio-ecological remediation where bacteria and fungi are employed to detoxify pollutants. Bacterial remediation reduces organic pollutants such as PAHs, pesticides, petroleum hydrocarbons, and phenolic compounds. For example, Pseudomonas, Bacillus, and

Rhodococcus are genera that have been described to transform xenobiotics by means of enzymatic reactions, mineralizing the pollutants to $CO_2$ and water under aerobic or facultative anaerobic conditions [22]. Mycoremediation employs saprophytic filamentous fungi, predominantly white-rot and brown-rot fungi, to biodegrade recalcitrant organic pollutants by excreting extracellular enzymes such as laccases, lignin peroxidases, and manganese peroxidases. Synthetic dyes and industrial solvents are degraded by white-rot fungi such as Phanerochaete chrysosporium and Trametes versicolor. Biosorption of heavy metals by fungi immobilizes them on the fungal cell wall or body, Apergilus and Penicillium were found to have high adsorption on Pb, Cd and Cr ions [23]. Novel approaches are combining microbial and fungal bioremediation with soil amendments, such as biochars, to promote pollutant bioavailability and microbial colonization. Biochar presented organic C network space for supporting microbial consortia and 301 adsorption of contaminants. These are microbial systems that employ bacterial-fungal communities to take advantage of the complementary metabolic capacities of the microorganisms for areas contaminated with EAs [24].

## 5. Constructed Wetlands and Ecohydrology-Based Systems

Constructed wetlands (CWs) are systems that are constructed to imitate natural wetlands for treating polluted water using physical, chemical, and biological functions (Kadlec and Wallace 2009). These systems employ FWS, HSSF, or VF to optimize the water–plant–microbe interplay. Treatment methods include sedimentation, filtration, adsorption, microbial decomposition, and plant absorption [24].

CWs are highly efficient for the treatment of, inter alia, domestic sewage, agro-industry effluents, landfill leachates and urban stormwater runoff. They decrease BOD, nutrients, heavy metals, and pathogens and are a low-maintenance option to traditional treatment. CWs exploit plant–microbe cooperation, such as plants (e.g., Phragmites australis and Typha latifolia) absorbing contaminants and enhanced microbial activity. In the root zone, microbial communities degrade pollutants. Reports suggest that there are favorable microbes to improve the pollutant degradation [26].

In Southeast Asia and Africa, CWs are used to treat agricultural runoff with fertilizers and pesticides. In addition, in India, a combined wetland system reduced nitrogen by 80% [27].

## 6. Advantages, Challenges, and Limitations of Bio-Ecological Remediation Technologies

Bioremediation technologies such as phytoremediation, microbial remediation, or mycoremediation and their combination systems have gained in recent years wide acceptance as promising green alternatives to physico-chemical technologies. The widespread use in soil and water environments contaminated by explosives has several advantages, but also operational and technical issues that need to be solved to allow their effective large-scale exploitation.

### Advantages

The cost is another of the major benefits of bio-ecological remediation. As opposed to soil excavation, incineration, and chemical oxidation methods, bioremediation does not require much investment in infrastructure or energy, making the process more applicable in less wealthy areas, particularly developing countries [6]. In addition, eco-friendly approaches, relying on living organisms (plants, fungi, microbes) that naturally degrade, convert, or immobilize contaminants, without generating toxic byproducts, have been studied. This biocompatibility improves public acceptability, particularly in rural and farming areas, where traditional remediation could disrupt local ecology. Furthermore, such technologies can often fit within the landscape or agricultural practices. For instance, phytoremediation may restore health to the soil and leave biomass that, for instance, can be directed to bioenergy, compost or nonfood applications [10].

### Challenges

Bio-ecological remediation methods, however, come with their limitations. Their slow speed in removing the pollutant is the main drawback, which leads to extended treatment periods, such as up to months and even years, especially for persistent pollutants, such as heavy metals and chlorinated organics [19]. Moreover, a number of these methods are also influenced by climate (temperature, humidity, rainfall) that modulate plant and microbial activity and may limit their effectiveness in arid or very cold regions. There are also concerns about bioaccumulation hazards in phytoremediation systems. Plants established for phytoremediation may become contaminated with toxic metals or organics in the process, resulting in disposal problems and potential ecological exposure if this biomass were to be eaten by herbivores or inadvertently introduced into the food chain [28].

### Technical and Operational Constraints

From an operational point of view, the site-specific character of bio-ecological remediation technologies can also provide a limitation. The effectiveness of phytoremediation or microbial decomposition is largely influenced by local soil chemistry, the speciation of the contaminants, and ecology, and therefore needs to be rigorously evaluated before implementation [28]. Furthermore, in large or highly polluted environments, e.g., rivers, indispensable biological conditions, i.e., sufficient nutrients, oxygen, and a sufficient presence of microbial diversity, cannot be satisfactorily sustained.

There is also a lack of regulations and standard protocols which hinder pilot studies from being translated to full-scale applications. Progress monitoring can also be less acute comparing with engineered systems, unless combined with modern biosensors or remote monitoring techniques [6].

## 7. Recent Advances and Emerging Trends in Bio-Ecological Remediation

### Use of Nanoparticles and Bio-Nano Hybrids

The addition of NPs into the bioremediation technologies has created a new era for the improvement of contaminant removal efficiency. Zero-valent iron (nZVI), silver (AgNPs), zinc oxide (ZnO), and magnetic iron oxide ($Fe_3O_4$) nanoparticles are adsorbent, catalytic, and suitable for degradation and reduction of pollutants. Additionally, bio-nano hybrids, in which nanoparticles are combined with microbial biomass, enzymes, or plant-based materials, have shown enhanced biocompatibility and function. For example, biochar-borne nano-Fe for heavy metal sequestration can also promote the substrates for the growth of microorganisms and their activity in soil ecosystems [30]. These hybrid systems also show great potential for multi-contaminant scenarios where the simultaneous occurrence of organic and inorganic species is observed.

### Genetic Engineering and Synthetic Biology for Enhanced Biodegraders

With the advent of synthetic biology and genetic engineering, engineered microbial strains have been developed to degrade better. Laccases, dehalogenases, oxygenases, and enzyme-encoding genes have been cloned and transferred to microbial hosts (*e.g.*, *Pseudomonas*, *Bacillus*, *E. coli*) to broaden the degradative spectrum and enhance resistance to toxic intermediates. In this regard, mixtures of engineered microorganisms have recently begun to be tested toward cooperative action for the elimination of sophisticated effluent and soil pollutants. New developments also include transgenic hyperaccumulator plants with better-root U and detoxification capacities [31] and microbes with inbuilt biosafety circuits, for escape proof removing the persistence in the environment.

### Monitoring Tools: Biosensors and Molecular Markers

Such remediation relies on the continuous monitoring of the pollutants as well as the biotic responses. The development of biosensors—devices which contain biological material such as enzymes, antibodies, or microorganisms—has revolutionized the detection of heavy metals, nitrates, or organic toxins. Fluorescent or electrochemical biosensors can be developed for the in-situ detection of trace contaminants at high sensitivity. Similarly, molecular markers such as 16S rRNA profiling and functional gene quantification (*e.g., alkB for hydrocarbon degradation*) are used to follow the dynamics and function of the microbial community in remediation sites. The combination of biosensor data with ecological indices further enables a better assessment of the remediation progress [32].

### AI and IoT in Monitoring Eco-Remediation Systems

The application of AI and IoT in environmental remediation is emerging. AI algorithms can also forecast how contaminants flow around, how different microbes interact, and how plants grow under stress, providing a way to identify the best kinds of remedial approaches. IoT sensors deployed in soil or water provide real-time data over variables like pH, nutrients, temperature, and pollutants. These cyber tools also enable pinpoint remediation and reduce inputs and environmental exposure. Recent pilot studies show that AI-based adaptive management systems can be used in constructed wetland and phytoremediation scenarios, resulting in faster response times and optimal ecological performance.

## 8. DISCUSSION

The increased burdens of environmental pollution drive the demand for cheap and sustainable remediation. This overview elaborates on the bio-ecological methods of cleanup, *viz*., phytoremediation, microbial and fungal remediation, vermiremediation, and ecohydrology-based technologies. It has been accepted as an applicable, simple, and cost-effective material; however, its efficacy varies with the type of plants, contaminants, and climate. The use of PC has been enhanced by plant hyperaccumulators, transgenic ones, and combinations with microbial inoculants [13, 18]. It also has the potential to biodegrade hydrocarbons, pesticides pharmaceutical residues through engineered bacteria and microbial consortium, but still faces the issue of biosafety [31].

Mycoremediation and vermiremediation contribute to organic matter decomposition and stabilization of heavy metals. Finally, persistent pollutants are decomposed by fungi and by earthworms by enhancing microbial activity [16, 12]. CWs are used for treating municipal wastewater, however, they present space and hydraulic constraints [17]. Nanoparticles and bio-nano hybrids increased the efficiency of pollutant removal. By combining biosensors, AI, and IoT, we may monitor in real time and decide on data [32, 34]. Yet, field heterogeneity, complex contamination, and resource limitations may present impediments to direct implementation.

Hybrid systems of biological treatment and intelligent monitoring will define the future of environmental bioremediation, extending the scope of remediation, but advocating for the further increase in biodiversity and carbon sequestration.

## 9. CONCLUSION

The magnitude of environmental pollution necessitates sustainable remediation methodologies. This paper focuses on bio-ecological approaches - phytoremediation, microbiological and fungal remediation, vermiremediation, rhizoremediation, and design-based treatment systems (constructed wetlands), each with their respective benefits to soil and water contaminants. Their efficiency is increased with an integrated strategy by using the synergic effect of plants-microorganisms, fungi, and soil fauna. Advances in nanotechnology, synthetic biology, and biosensor-based monitoring feeding into AI and the internet of things are underpinning smart, adaptive eco-remediation platforms. These novel features facilitate both real-time surveillance, targeted pollutant treatment, and ecological reinforcement. There are significant challenges in deploying at scale, from seasonally varying field conditions and regulatory restrictions to economic limitations and studies of ecosystem impact. The future research agenda must be designed based on field-scale validation and policy matching to make these green technologists a real-world solution. Bio-ecological remediation processes are the way forward toward environmental sustainability. Their integration with new tools may lead to robust strategies for soil and water recovery in the face of global environmental challenges.

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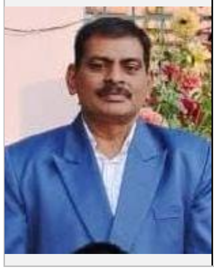

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