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CUTTING EDGE USE OF MICROBIAL CONSORTIA FOR BIOREMEDIATION OF CONTAMINATED SOIL

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Abstract

Ecosystems and human health are both significantly impacted by soil contamination which is a serious environmental problem. It entails the presence of variety of organic and inorganic compounds, including radionuclides, phthalates, pesticides, heavy metals, and polycyclic aromatic hydrocarbons (PAHs). These toxins come from places like mining operations, manufacturing facilities, agricultural operations, and waste management systems. It is a difficult undertaking that necessitates the use of effective and eco-friendly technology to remediate contaminated soils. A potential method for improving bioremediation is the employment of microbial consortia, which are groups of various microbial species or genera. Microbial groups can work together through interactions to degrade a variety of contaminants and they can also change their composition or activity to respond to shifting environmental conditions. There has been evidence that some types of bacteria, fungi, and algae can degrade soil contaminants. The creation and application of microbial consortia for soil bioremediation still face difficulties and information gaps, though. These involve comprehending and enhancing metabolic interactions and pathways, enhancing the bioavailability and biodegradability of pollutants, and evaluating the ecological impacts and hazards of introducing bacteria. In this study, the potential of microbial consortia for the bioremediation of soil contaminants is highlighted, along with information on the benefits, drawbacks, and potential future directions for research and development.

Keywords: contaminated soil, microbial consortia, remediation, soil health and contaminants

INTRODUCTION

One of the most devastating environmental issues today is soil contamination, which has adverse impact on ecosystem services and human health (Raimi et al., 2022, Singh & Signh, 2020). Organic and inorganic chemicals such as radionuclides, phthalates, pesticides, heavy metals, and polycyclic aromatic hydrocarbons (PAHs) are examples of soil contaminants (Di Fiore et al., 2023, Tyagi & Kumar, 2021, Shourie & Vijayalakshmi, 2022; Dua et al., 2002). These contaminants emanate from a variety of sources, including mining sites, industrial processes, agricultural methods, urban waste management, and unintentional spills (Cachada et al., 2018). Remediating contaminated soils is a difficult task that warrants efficient and environment friendly technologies.

A potential method called bioremediation uses microorganisms to break down, change, or immobilize soil contaminants. In order to transform soil contaminants into less harmful or more accessible forms, microorganisms have the ability to use them as carbon and energy sources, electron donors, or acceptors (Sama et al., 2022, Kumar et al., 2018, Kulshreshtha et al., 2014). Thus, bioremediation offers a competent strategy for alleviating environmental contamination despite the slow process it represents. Optimizing environmental factors including pH, temperature, moisture, oxygen availability, and nutrients supply can improve bioremediation (Kebede et al., 2021). The addition of exogenous microorganisms, surfactants, enzymes, or electron shuttles, can also promote bioremediation.

Although bioremediation is a slow process, it is also hindered by the complexity, diversity, and interactions of soil contaminants with the soil matrix and microbial communities, frequently placing limits on the bioremediation of soil contaminants (De la Cueva et al., 2016). The bioavailability and biodegradability of many soil contaminants are hampered by their resistance to degradation, hydrophobicity, or poor solubility. The effectiveness of bioremediation can also be impacted by the synergistic or antagonistic effects that particular soil contaminants might have on microbial diversity and activity (Kumar et al., 2021; Sayara & Sánchez, 2020). Therefore, thorough knowledge of the microbiological mechanisms and processes involved in contaminant breakdown and transformation is necessary for enhancement of bioremediation of soil contaminants.

The existence and activity of an appropriate microbial consortia is one of the critical components that will affects bioremediation success (Kebede et al., 2021). A microbial consortium is any two or more microbial communities of distinct species or genera acting synergistically in a complicated system (Xu et al., 2020) which can be natural or artificial. For enhanced bioremediation of soil contaminants, a microbial consortium can be more advantageous than a single strain in a number of ways. By expressing complementary metabolic pathways or enzymes, a microbial consortium, degrade a broader variety of contaminants or complicated combinations of contaminants, cooperate through syntrophic interactions, cross-feeding, co-metabolism, or quorum sensing to increase the degradation efficiency or rate, by promoting their additional destruction or detoxification, thus reducing the buildup of hazardous intermediates (Bhatt et al., 2021). Modifying the activity or composition of microbial consortium through selection or control in order to cope with dynamic environmental conditions (Santoyo et al., 2021; Adam, 2016). By introducing tolerance or resistance mechanisms, one can fend off the inhibitory effects of contaminants or other stressors.

The potential of microbial consortia for the bioremediation of soil contaminants has been shown in numerous researches. For instance, microbial consortia have been employed to decontaminate heavy metals, pesticides, phthalates, PAHs, and crude oil in polluted soils (Zhang & Zhang, 2022). It has been discovered that certain bacteria, including *Lactobacilli*, *Actinobacteria*, *Pseudomonas, Clostridium, Salmonella,* and *Escherichia coli*, have the innate capacity to breakdown contaminants (Bhatt et al., 2021).

The development and use of microbial consortia for the bioremediation of soil contaminants still has numerous obstacles and knowledge gaps. According to Xu et al. (2020) the development of effective and stable microbial consortia from natural or contaminated soils involves characterizing and optimizing their metabolic pathways and interactions involved in pollutant degradation, evaluating and enhancing the bioavailability and biodegradability of soil pollutants by microbial consortia, and assessing and monitoring the ecological effects and risks of introducing microbes.

Given the challenges of developing a best-fit microbial consortium to aid soil contaminant breakdown, this review paper encapsulates a comprehensive summary of recent findings regarding the use of microbial consortia for the bioremediation of soil contaminants. The review discusses the following subjects: the primary types and sources of soil contaminants and their effects on soil quality and human health; the principles and mechanisms of bioremediation by microorganisms; the role of microbial consortia in degrading specific contaminants; the benefits and difficulties of using microbial consortia for bioremediation of soil contaminants.

TYPES OF SOIL CONTAMINANTS, THEIR SOURCES, AND HOW THEY AFFECT BOTH HUMAN HEALTH AND SOIL QUALITY

There are two basic categories of soil contaminants: organic and inorganic. Polycyclic aromatic hydrocarbons (PAHs), insecticides, herbicides and petroleum-based substances are examples of organic pollutants (Chaurasia et al., 2019, Thomas et al., 2022). These contaminants come from traffic, urban garbage, industrial processes, and agricultural activities (Song et al., 2017). The fertility of the soil, microbial activity, plant development, and animal health are all impacted by soil contaminants (Akram et al., 2018).

Non-carbon-containing metals and salts like arsenic, mercury, lead, cadmium, zinc, nickel, copper, selenium, beryllium, thallium, and chromium, are examples of inorganic contaminants generally referred to as heavy metals. These contaminants emerge from irrigation, industrial waste, mining, and medical waste. Inorganic contaminants have the ability to change the pH, salinity, structure, and availability of nutrients in the soil (Vocciante et al., 2022). They accumulate in plants and animals, resulting in toxicity, or imbalances. Arsenic and mercury are two examples of inorganic contaminants which are neurotoxic and harmful to the nervous system of humans when are ingested (de la Cueva et al., 2016)

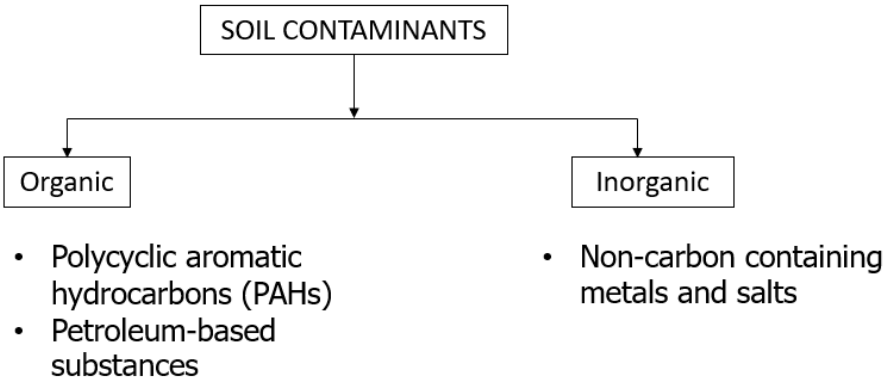

Figure 1. Types of soil contaminants

Numerous detrimental effects of soil contamination on soil quality and public health exist. The physical, chemical, and biological characteristics of the soil are among the key components often adversely affected by soil contaminants, resulting in reduced soil quality and poor agricultural yield (Mishra et al., 2019). Often, the soil surface contaminants find their way into water bodies, contaminating sub-surface and groundwater. Unscrupulous use of agrochemicals on crops endangers the safety of food jeopardizing human health (Mahurpawar, 2015). More so, exposure to soil contaminations by humans and animals can trigger acute or chronic illnesses like cancer, neurological disorders, birth defects, migraines, nausea, skin irritation, respiratory and cardiovascular issues, and headaches (Manisalidis et al., 2020; Onakpa et al., 2018).

MICROBIAL CONSORTIA

A microbial consortium refers to any two or more microbial communities of various species or genera acting in synergy within a complex dynamic system (Xu et al., 2020). In comparison to single cultures, bioremediation using microbial consortia has a number of benefits, including increased mineralization efficiency, increased diversity, microbial community resilience, and stability (Bhatt et al., 2021, Santoyo et al., 2021, Adam, 2016). The microbial consortia can be assembled using a variety of techniques and resources, including enrichment cultures, natural habitats, genetic engineering, and synthetic biology (Gilmore et al., 2019). Depending on the types of microorganisms involved and the environmental conditions, they can have a variety of structures, functions, and dynamics.

PRINCIPLES AND MECHANISMS OF MICROBIAL BIOREMEDIATION

Bioremediation is the process of breaking down harmful environmental contaminants into less dangerous or harmless substances using microorganisms. Organic and inorganic contaminants can be metabolized by microorganisms including bacteria, fungi, algae, and protozoa by utilising them as sources of carbon, energy, or electrons (Gajda et al., 2015). Different contaminated environment, including soil, water, air, and sediments, can be treated via bioremediation. The four basic steps in the principles of microbial bioremediation are as described by Ławniczak et al. (2020) and Azubuike, et al. (2016). The biodegradation processes can involve a variety of reactions, including oxidation, reduction, hydrolysis, dehalogenation, and methylation, and they can be either aerobic (requiring oxygen) or without oxygen, anaerobic (Chunyan et al., 2023, Kumar et al., 2018).

The mechanism of action involves both extracellular and intracellular processes which are the two primary divisions of bioremediation by microorganisms. The uptake and breakdown of contaminants inside the microbial cells is referred to as intracellular bioremediation (Saravanan et al., 2021). Several processes, including oxidation, reduction, hydrolysis, dehalogenation, methylation, and demethylation, can lead to this. Carbon dioxide, water, and biomass are typical byproducts of intracellular bioremediation (Saravanan et al., 2021). *Pseudomonas* spp. degrading petroleum hydrocarbons, *Burkholderia* spp. degrading polychlorinated biphenyls (PCBs) and *Rhodococcus* species degrading nitroaromatic substances are instances of intracellular bioremediation (Kuyukina & Ivshina, 2016).

By using enzymes or other compounds released by the microorganisms, extracellular bioremediation entails transforming contaminants outside of the microbial cells. This can happen by a number of different methods, including bioleaching, bio-sorption, bioaccumulation, biosynthesis, and bio-mineralization. Extracellular bioremediation typically results in less harmful or more soluble forms of the contaminants as its final products (Saravanan et al., 2021). The bio-sorption of heavy metals by algae and fungi, the bioaccumulation of radionuclides by bacteria and fungi, the biosynthesis of nanoparticles by bacteria and fungi, the bio-mineralization of arsenic by bacteria, and the bioleaching of metals from ores by bacteria are some examples of extracellular bioremediation (Amin et al., 2021).

SOME EXAMPLES OF APPLICATIONS OF MICROBIAL CONSORTIA FOR CONTAMINANTS DEGRADATION

Tables 1. Examples of application of microbial consortia in biodegradation of contaminants

Contaminants	Examples of Microbial constituents	Remarks	References
Polycyclic aromatic hydrocarbons (PAHs)	*Klebsiella pneumoniae, Bacillus cereus, Pseudomonas aeruginosa, Klebsiella* sp., and *Stenotrophomonas maltophilia*	These five groups of bacteria consortia have been shown to accelerate the degradation of PAHs.	Zafra et al., 2016
	PA-OBP1, PA-OBP2, PA-OBP3, and PA-OBP4	These strains of *P. aeruginosa* release a wider range of enzymes to catalyze the complex breakdown process of PAHs	Ma et al., 2021
	A mixture of algae, bacteria, and fungi	The photosynthetic algae provide bacteria and fungi with nutrients and oxygen. Together, these bacteria can degrade PAHs more quickly and efficiently than any one of them could on its own	Al-Hawash et al., 2019
Crude oil	Fungi*; Scedosporium boydii,* and bacteria*; Paraburkholderia tropica*	These two microorganisms significantly increase the biodegradation of crude oil from 61.06 % to 81.45 % under specified co-cultivation conditions and the bacteria to fungus inoculation ratio of 3:1.	Yuan et al., 2018
Bisphenol S (BPS)	Bacterial consortium; *Pseudomonas umsongensis, Bacillus mycoides, Bacillus eihenstephanensis, Bacillus subtilis* and fungal consortium; *Mucor circinelloides, Penicillium daleae, Penicillium chrysogenum, Aspergillus niger,*	The bacterial consortium raises the activities of catalase, urease, acid phosphatase, and alkaline phosphatase. The fungal consortium enhances the dehydrogenase, arylsulfatase, b-glucosidase, and acid phosphatase activities.	Zaborowska et al., 2019
Pesticides	A consortium of *Diaphorobacter sp.* LR2014-1 strain and *Achromobacter sp*	The latter first hydrolyzed linuron to 3,4-dichloroanaline, the former first mineralized the resultant aniline derivative	Zhang et al., 2020, Öztürk et al., 2020, Zhang et al., 2018

	Aspergillus fumigatus, *A. nelson,* *A. endosulfan,* *Rhizopus microsporus var. corymberifera microsporis,* *Terreus spp.,* *Absidia spp., and* *Trichoderma viridae*	These fungi biodegrade methyl parathion insecticides.	Soares et al., 2021
Triphenyl Phosphate (TPHP)	microbial consortium GYY, consisiting of the bacteria *Pseudarthrobacter, Sphingopyxis, Methylobacterium*, and *Pseudomonas*	TPHP was metabolized by hydrolysis, and methoxylation following the activation of the hydroxylation pathways. 92.2% of TPHP can be broken down in 4 hours under ideal circumstances	Yang et al., 2020, Wang et al., 2021
Cadmium (Cd)	genus *Bacillaceae,* and *Sporosarcina* sp	They have the ability to convert Cd^{2+} into carbonate. During the urease hydrolysis of urea, these bacteria bind Cd^{2+} cations because of their negative charges, and the Cd^{2+} and carbonate combination finally precipitates	Yin et al., 2021, Belimov et al., 2020, Ketoky & Pandey, 2020

ADVANTAGES OF USING MICROBIAL CONSORTIA

According to Gupta et al. (2016) and Tyagi & Kumar (2020) the advantages of using microbial consortia are summarised in the table below.

Table 2. Advantages of application of microbial consortia in bioremediation

S/N	**Advantages**
1	Microbial consortia have a wider range of metabolic processes than do individual bacteria. This implies that they can effectively act across larger variety of contaminants
2	The biodegradation process has redundancy due to the group of microorganisms. Some species in the consortium may be able to decompose a specific contaminant if another one is unable to do it
3	A consortium of microorganisms' interactions with one another can improve the consortium's capacity to break down contaminants
4	To ensure ongoing and effective biodegradation, they may adapt to various environmental factors and contaminants
5	When compared to more conventional remediation techniques, such as chemical treatments, the utilization of microbial consortia for bioremediation is less expensive. Microbial consortia are simple to produce and can be used locally, saving money on transportation
6	Microbial consortia are environmentally beneficial and do not produce any negative by-products

DIFFICULTIES OF BIODEGRADATION BY MICROBIAL CONSORTIA

The use of microbial consortia is a technique for bioremediation that shows promise, but it also has significant issues that need to be resolved. Some of the difficulties encountered during the use of microbial consortia have been summarized in Table 3 (Boopathy, 2000).

Table 3. Difficulties in using Microbial Consortia in Bioremediation.

Variables	**Explanation**
Availability of resources	Microbial consortia need a steady stream of nutrients to support their metabolic activities. A lack of nutrients might result in decreased microbial activity, which can harm the biodegradation process. Therefore, other nutrients being needed by the microbes must be made available for their efficient work
Competition among microbial species	In a microbial consortium, many microbial species contend with one another for resources including oxygen, nutrients, and space. The overall effectiveness of the biodegradation process may be impacted by the dominance of one microbial species over the others as a result of competition
Monitoring and control	Due to diversity of microbial community and our limited understanding of how various microbial species interact, monitoring and managing of biodegradation process can be difficult. To be successful and efficient the biodegradation process requires precise monitoring and control
Others	Microbial activity can be impeded by a number of factors, including harmful substances, high pollution concentrations, and environmental stressors. The pace of biodegradation can be slowed down by microbial activity inhibition or the process may potentially fail entirely. So, the proper monitoring on these stressors is required

THE FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS FOR IMPLEMENTING MICROBIAL CONSORTIA FOR BIOREMEDIATION OF SOIL POLLUTANTS

While there are advantages to using microbial consortia for bioremediation of polluted soils, there are also challenges and information gaps. Future studies should concentrate on creating novel methods to extract, characterize, and engineer desired microbial consortia in order to improve this subject. It is crucial to comprehend the ecological and evolutionary mechanisms governing consortia in polluted soil. It is essential to look into how contaminants and consortium members interact at the molecular level and how this affects degradation pathways. It is vital to examine how microbial consortia-based bioremediation affects ecosystem services, biodiversity, soil quality, and human health. The management of sustainable soils and environmental protection can both be considerably aided by addressing these research directions.

CONCLUSIONS

The biodegradation due to microbial consortia has potential for bioremediation, but it needs close supervision. Continuous monitoring and environmental changes can be used to maintain stable composition and structure. Competition can be reduced by consortium member selection and management, while nutrient availability can be managed by supplying nutrients and growth factors.

Examining environmental conditions and taking into account detoxification and dilution techniques are necessary for the inhibition of microbial activity. Accurate management and monitoring are essential for effective biodegradation. Understanding microbial interactions is aided by transcriptomics and metagenomics, and the process optimization is boosted by real-time monitoring. For microbial consortia biodegradation to be successful in environmental remediation, interdisciplinary cooperation in engineering, environmental science, and microbiology is essential.

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