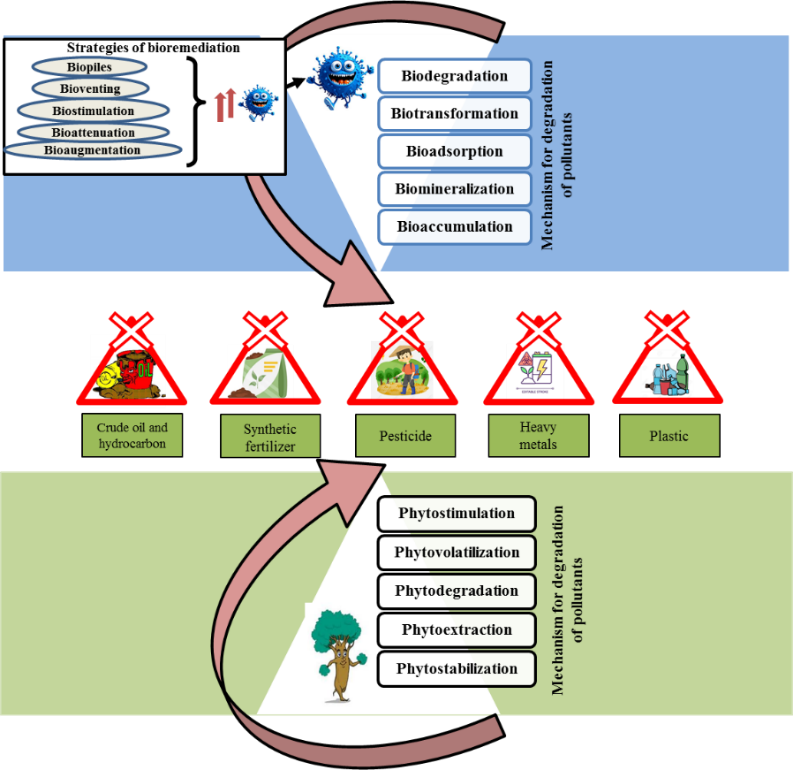
***Review Article***

**ADVANCED SUSTAINABILITY THROUGH THE PLANT AND MICROBIAL REPROGRAMMING IN BIOREMEDIATION OF AGRICULTURAL SOIL**

ABSTRACT

Bioremediation is an eco-friendly approach that utilizes microbes and plants to effectively remove a wide range of pollutants from the soil. Various strategies—such as bioventing, biopiling, biostimulation, bioattenuation, and bioaugmentation—are employed to enhance biological processes, breaking down complex soil contaminants into simpler, non-toxic forms. These byproducts are absorbed by plants and microorganisms, contributing to a healthier environment. While extensive research exists on bioremediation techniques and microbial mechanisms, reports on their practical applications and proven benefits remain limited. Therefore, developing effective bioremediation strategies is crucial to degrade pollutants at scale, preserve nutrient availability, and optimize microbial populations and processes, including biodegradation, biosorption, biomineralization, bioaccumulation, and biotransformation, tailored to specific contaminants. This paper reviews various bioremediation approaches and their potential as viable solutions for addressing emerging environmental pollutants. With continued advancements, microbial and phytoremediation couldmitigate pollution and promote long-term environmental health

**GRAPHICAL ABSTRACT**



**Keywords:** Bioremediation, Contaminants, Bioremediation strategies, Microbial remediation, Phytoremediation.

**1. INTRODUCTION**

On a global basis, soil pollution gets a lot of attention, particularly in slag disposal areas, specialized industrial wastelands, and agricultural farmland. Soil contamination is rapidly increasing with the development and growth of the population due to anthropogenic activities such as urbanization and industrialization. Presently, fertilizer or pesticide application, synthetic chemical manufacturing, fossil fuel burning, and mining are the worst causesof soil contamination such as heavy metal deposition (Tang et al. 2019) pesticide residue (Song et al. 2019), and hydrocarbon (Hoang et al. 2021). Heavy metal pollution, typically coexists with organic pollution of many types, such as pesticides, endocrine disruptors, petroleum, and their derivative. Heavy metals and organic contaminants are carcinogenic and mutagenic and persist for a long time in soil which has negative impact on soil ecology (Zeng et al. 2013).

The transport and transformation mode of pollutants in soil, as well as their reactions to remediation technology, varies due to the physical and chemical features of various contaminants. Furthermore, the interactions between numerous contaminants in soil build up a more complicated remediation process. For example, interactions between heavy metals and organic contaminants may alter pollutant speciation, volatility, and bioavailability, reducing or enhancing each other's remediation efficiency (Jin et al. 2013). The microbial communities and plants would suffer dual stress and severely reduce their biomass and biodegradability of contaminated soil. Heavy metal concentrations above a certain threshold tend to impair microbial metabolism and enzymatic activity, lowering the efficiency with which organic contaminants are degraded (Dong et al. 2013). The presence of pollutants in soil not only adversely affects plant development but also impacts soil texture, structure, and nutrient cycling along with the diversity, activity, and composition of microbial communities(Sivaram et al. 2018). Multiple contaminants cause pollutant accumulation and amplification effects in organisms through the food chain, which is hazardous for wildlife, humans, and natural ecosystems. As a result, decontamination is necessary to improve the efficiency of contaminated ecosystems.

Based on these circumstances, extensive research has been performed to minimize the issue of contaminants and develop effective remediation strategies simultaneously reducing diverse pollutants such as physical, chemical, and biological**.** Physicochemical strategies such as chemical oxidation, soil washing, nanomaterial, and electrokinetic remediation are all likely to harm the soil ecology by causing changes in pH and moisture as well as greater oxidation potential (Cheng et al. 2016). Bioremediation strategies include applying microbes and plants to convert heavy metal into bioavailable form and decomposition of synthetic and organic contaminants (Zhu et al. 2012). Biological remediation is more suited and cost-effective for large-scale in situ cleanup as compared to physicochemical approaches. They ensure ecological sustainability by enhancing the ability of microbes to increase the soil quality and their functions. Keeping the above crucial consideration, the aim of this review is to find out the various soil bioremediation strategies and their significant role in the degradation of synthetic and organic contaminants and heavy metal passivation. This review aims to: (1) explore bioremediation strategies for addressing multiple contaminants, (2) elaborate on the mechanisms involved in the bioremediation of heavy metals, as well as organic and inorganic pollutants, and (3) conclude with the current needs and future directions for research in this field.

**2. TYPES OF CONTAMINANTS AND THEIR SOURCE IN SOIL**

**2.1 HEAVY METALS**

The increasing level of heavy metal pollutants has resulted in a slew of negative consequences for our natural ecosystem. The amount of mercury, lead, cadmium, chromium, and arsenic has attracted increasing attention than any other heavy metal contamination in our environment. Because they are non-threshold poisons and present greater quantities in terrestrial, aerial, and aquatic ecosystems (ATSDR 2015). Rahman and Singh (2019) revealed that high concentration of these heavy metals (As, Cd, Hg, Pb) in soil impose negative impact on plant growth and development as well as soil habitat. Currently, Cd, Cr, Hg, and Pb from diverse anthropogenic activities are estimated to constitute an outsized harm to 66 million people worldwide (Pure Earth 2015).

**2.2 PESTICIDE**

Pesticides incorporate different types of synthetic products such as fungicides, insecticides, nematicides, herbicide, rodenticide which are applied in agriculture field for pest control (Tsaboula et al. 2019). Presently in the modern agriculture, application of pesticide plays an important role in crop production and frequently utilized in all sector of agriculture, to improve the crop productivity and economic benefits. Furthermore, excessive application of pesticide could result in a significant rise in and buildup of pesticides in the environment, posing a serious threat of pesticide contamination (Song et al. 2019). Pesticides are widely used and influence practically all crops such as orchards, vineyards, cereals, olive groves, and vegetables in various forms and at different seasons, where they can move into the soil, soil surface, and ground water, contaminating these natural systems (Close et al. 2021).

**2.3 SYNTHETIC FERTILIZER**

Chemical fertilizers are synthetic substances that contain the high nutrient concentrations required for plant growth and development. These are man-made fertilizers that provide the required plant nutrient for higher crop yield. Fertilizers and other chemical products are inherent dangers in agriculture. Nonetheless, they remain critical tools for global food security, and their negative consequences cannot be overlooked, especially given the global target of sustainable agriculture. The chemical fertilizers play vital role in enhancing the crop productivity along with soil fertility. In agriculture, only 10% to 40% applied fertilizer can be directly utilized by plant and remaining fertilizers are available in insoluble form as inorganic salt which accounts a great threat for soil biodiversity (Zheng et al. 2019). Therefore, unreasonable long-term use of chemical fertilizers increases environmental pollution and soil aciditywhich has negative impact on crop yield and quality along with soil biodiversity(Battaglia et al. 2021; Seleiman et al. 2021).

**2.4 PLASTICS**

Plastic is a conveniently available, cost-effective, and accessible material which is commonly used in industries and in our daily lives all over the world, and they provide a great deal of convenience to humanity. Presently, it is undeniably due to increasing plastic production levels, use and disposal patterns, minimal recovery rates, and demographic details all are leading to an increase in plastic waste accumulation in the environment (Kumar et al. 2021). Even though plastics are persistent, only about 5% of them are recycled (Kumar et al. 2020). Brahney et al. (2020) estimated that the increasing utilization and demand of plastics will accumulate about 11 billion tonnesof plastic waste material in our environment by 2025. Surface embrittled plastics are micro-cracked by microbial-mediated, weathering conditions and mechanisms such as UV light and hydrolysis, and are increasingly degraded into small fragments term as microplastics, which are projected to cause severe environmental problems over a hundred years (Auta et al. 2017). Microplastic is called “white pollution” because of plastic garbage pollutes the ecosystem and will not disintegrate in the natural environment for at least 100 years (Ricardo et al. 2021).

**2.5 CRUDE OIL AND HYDROCARBON**

Hydrocarbons are naturally occurring organic substances that are mostly produced from plant and animal fossils as a result of natural or human-caused processes. They are made up of carbon and hydrogen and serve as the basis for natural gas, crude oil, and coal, which provide a major amount of the world's energy. They contain many hazardous chemicals such as toluene, ethylbenzene, xylene, naphthalene, benzene etc. which is harmful tosoil, plants, and human life. Intentionally or accidentally, hydrocarbon and their derivatives product are released into soil and oceans and primarily existed in three physical state such as solid, liquid and gas(Liu et al. 2019). Hydrocarbon and crude oil contaminants has taken on a worldwide scale because of the hazard it represents to all life form such as soil microbes, animals and human as well as groundwater quality. The hydrocarbon and their derivative adversely affect the environment. Thereby, the ecosystem's functioning along with its living microflora and nonliving components, deteriorates as a result of hydrocarbon contamination (Essabri et al. 2019).

**3. SIGNIFICANT ROLE OF MICROORGANISMS AND PLANTS IN BIOREMEDIATION**

Soil microorganisms play an important role in cleaning and reclamation of contaminated soil for enhancing the degradation of toxic pollutants such as hydrocarbon, pesticides, heavy metals, and plastics (Verma et al. 2014). Soil rhizomicrobiome as a plant growth promoting rhizobacteria (PGPR) facilitates the bioremediation process along with plant growth mechanism through directly or indirectly in polluted soil. According to Thavamani et. al. (2015), bacteria with the capacity for hydrocarbon metabolism and Cd tolerance displayed outstanding remediation capabilities in soil that had been contaminated by a variety of various contaminants. In tests for bacterial accumulation, Cd2+ (chemisorption) and Zn2+ (physisorption) were found to be primarily adsorbed onto the cell walls rather than accumulating inside the bacteria. Additionally, chelators, surfactants, and organic acids released by soil microbes are explored as modifying techniques to regulate the bioavailability of pollutants during the microbial remediation process in polluted soil. Moreover, the enzyme activity of soil microbes may efficiently remove pollutants such as petroleum hydrocarbons, polychlorinated biphenyls, Zinc, Lead, organophosphates, organochlorines, and carbamates (Sharma et al. 2018).

Phytoremediation is a plant-based mechanism using green and living plants to remove pollutants from a contaminated environment. Phytoremediation is recommended as cost effective, eco-friendly and economic remediation process for our environment. Plants depict their capabilities to absorb soil pollutants (organic pollutants, pesticide, heavy metals) at very low concentrations. They expand their root system and set up their rhizosphere eco-system into a soil matrix for translocation or accumulation of pollutants and regulate their bioavailability, thereby reclaiming the soil fertility (Jacob et al. 2018). Meanwhile, exudates released by plant roots attract abundance microbial populations which contributes to the degradation of pesticide residual. For example, differentgenotypes of *Ricinus communis* (castor) removed the Cd and DDTs from contaminated soil (Huang et al. 2011). Similarly, *Zea mays* plants showed a strong removal capacity of benzene and also removed 97 % of pesticides e.g. atrazine in soil (Feng et al. 2017). Various plants such as *Cucurbita pepo, Lolium perenne, Spinacia oleracea,*and *Medicago sativa L.* have revealed their capacity to degrade pesticides, organic pollutants, and heavy metals from contaminated soil (Zhang et al. 2019).

**4. BIOREMEDIATION STRATEGIES**

There are some treatment strategies of contaminated soil which has described by Rajendran and Gunasekaran(2019).

**4.1 BIOSTIMULATION**

This type of strategy involves the addition of particular nutrients and growth regulators to the contaminated soil and water to promote the activity of microorganisms. Moreover, environmental conditions such as oxygen, temperature, and pH enhance their metabolic activity (Adams et al. 2015).

**4.2 BIOATTENUATION**

Natural attenuation is the removal of maximum pollutants from a contaminated area using biological (aerobic and anaerobic biodegradation), chemical reaction (complexion and ion exchange), and physical (volatilization, sorption, diffusion, dilution, advection, and dispersion) (Li et al. 2010).

**4.3 BIOAUGMENTATION**

Bioaugmentation includes the incorporation of pollutant-degrading microbes which may be exotic and genetically modified to increase the biodegradation process of contaminants and also augment the metabolic pathway of indigenous microbial communities. Microorganisms are isolated from the contaminated site, cultivated separately, genetically altered, and then released back onto the site. For evidence, soil and groundwater contaminated with trichloroethylene and tetrachloroethylene result in the presence of all necessary microorganisms in contaminated areas. It is utilized to make sure that the in-situ microbes can eliminate and transform these pollutants into non-toxic ethylene and chloride (Niu et al. 2009).

**4.4 BIOVENTING**

Bioventing involves venting oxygen into the soil to promote the growth of native and introduced bacteria and fungi by supplying soil microbes with oxygen. It works with chemicals that degrade aerobically. Low airflow rates are used in bioventing to deliver just enough oxygen to support microbial activity. The most typical method of supplying oxygen is direct air injection into the soil with residual pollution using wells. As vapors flow slowly through biologically active soil, adsorbed fuel residuals and volatile chemicals are both biodegraded. Agarry et al. (2015)demonstrated that hydrocarbon-contaminated soil may be effectively bio-remediated through bioventing.

**4.5 BIOPILES**

Using biopiles is a method of storing excavated soil tainted with hydrocarbons that can be remedied aerobically. During the biodegradation process, biopiles (also called bioheaps, biocells, biomounds, and compost piles) are employed to lower petroleum concentrations in excavated soils. A system of pipework and pumps that either pushes air into the biopile under positive pressure or pulls air through the pile under negative pressure is used to supply air to the biopile system during this process. The breakdown of adsorbed petroleum pollutants increased as a result of increased microbial activity due to microbial respiration (Emami et al. 2012).

**5. REMEDIATION MECHANISM OF MICROORGANISMS AND PLANTS**

The persistent metals, hydrocarbon, plastics, synthetic fertilizers and pesticides in soils have escalated into a severe environmental concern because to their widespread use in industries and agriculture activities. Microbes have a lot of protective mechanism against toxicity of pollutants in contaminated soil.  An effective and promising method to clean up contaminated soils is known as bioremediation, which uses active microbes (Table 1) and plants (Table 2) to remove contaminants from soil (Fenner et al. 2013).

**Table: 1 Microorganisms Involved in the Remediation of Pollutants**

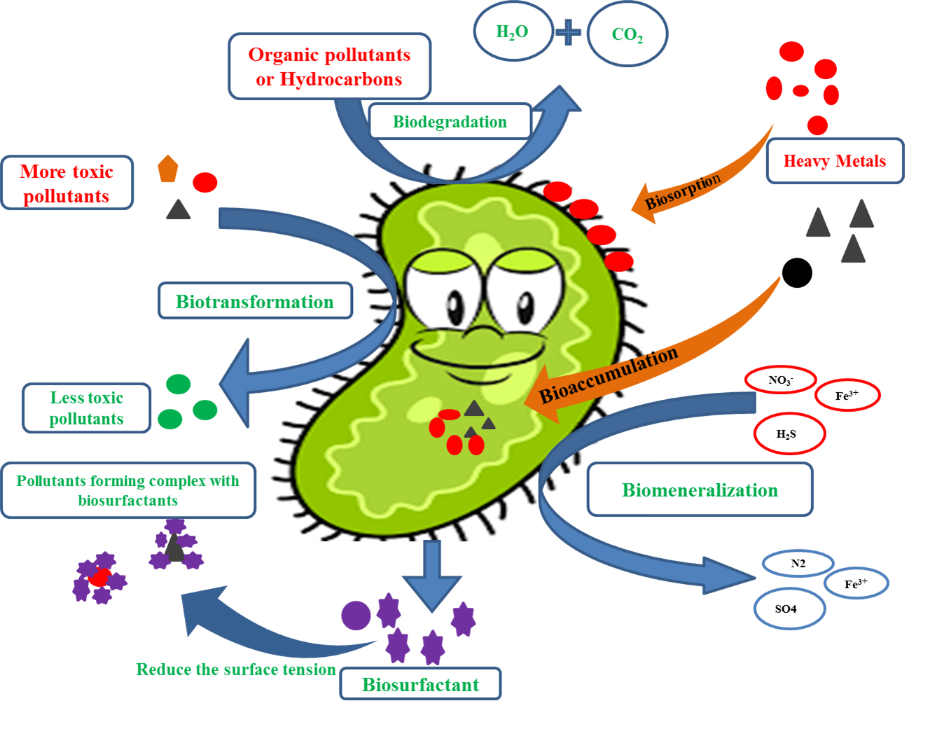
|  |  |  |
| --- | --- | --- |
| **Pollutants** | **Used microbes** | **Reference** |
| **Heavy metals** | | |
| Cd | *Bacillus safensis* | Priyalaxmi et al. (2014) |
| Cu, Cr, Ni, U | *Pseudomonas aeruginosa* and *Aeromonas*sp. | Sinha et al. (2011 |
| Cr, Cd, Pb | *Rhodopseudomonas palustris and Aerococcusspp.* | Sinha et al. (2014) |
| Zn, Mn, Fe, Pb and Cu | *Pseudomonas aeruginosa and Pseudomonas fluorescens* | Paranthaman and Karthikeyan (2015) |
| **Pesticide** | | |
| Fitoraz WP 76, Malathian, Ridimil MZ 68, Decis EC 2.5 | *Pseudomonas putida, Arthrobacter sp. and Acinetobacter spp.* | Monica et. al. (2016) |
| Endosulfan | *Staphylococcus and Bacillus* | Mohamed et al. (2011) |
| Methyl parathion and Chlorpyrifos | *Pseudomonas spp., Acenetobactor spp., Photobacterium spp. and Enterobacter spp.* | Ravi et al. (2015) |
| **Hydrocarbons (Organic pollutants)** | | |
| Dibenzofurans, Methylnaphthalenes, and PAHs, | *Coprinellus radians* | Aranda et al. (2010) |
| Benzopyrene and Phenanthrene, | *Candida viswanathii* | Hesham et al. (2012) |
| Benzene, ethyl benzene, toluene, xylene and phenol compounds | *Penicillium chrysogenum* | Pereira et al. (2014) |
| Aromatic hydrocarbons | *Pseudomonas, Ralstonia, Acinetobacter* and *Microbacterium* | Simarro et al. (2013) |
| Phenol | *Bacillus subtilis, Alcaligenes odorans, Pseudomonas aeruginosa, Corynebacterium propinquum*, | Singh et al. (2014) |
| Biphenyland triphenylmethane | *Phanerochaetechrysosporium* | Erika et al. (2013) |
| **Oil contaminants** | | |
| Crude oil | *Bacillus brevis, Bacillus licheniformis, Bacillus sphaericu and Pseudomonas aeruginosa* | EI-Borai et al. (2016) |
| Crude oil and Diesel oil | *Bacillus coagulans, Bacillus cereus, Pseudomonas cepacia, Serratia ficaria and Citrobacter koseri* | Kehinde and Isaac (2016) |
| Diesel oil | *Pseudomonas putida, Pseudomonas aeruginosa, Bacillus and Arthobacter* | Sukumar and Nirmala (2016) |
| Crude oil | *Fusarium spp*. | Hidayat and Tachibana (2012) |

**Table: 2 Plants involved in the remediation of pollutants**

|  |  |  |
| --- | --- | --- |
| **Pollutants** | **Used plant** | **Reference** |
| Cr | *Pteris vittaia* | Kalve et al. (2011) |
| Pb | *Euphorbia cheiraadenia* | Chehregani and Malayeri(2007) |
| Ni | *Alyssum markgrafii* | Bani et al. (2010) |
| DDT, Nitrates and Explosives compound | *Elodea canadensis* and Duckweed, | Newman and Reynolds (2004) |
| Xenobiotic substances | Cannes | Subramanian et al. (2006) |
| Atrazine | *Zea mays* | Ibrahim et al. (2013) |
| Triazophos | *Iris pseudacorus* | Li et al. (2014) |
| Toluene, Benzene, xylenes and ethylbenzene | Canna × Generalis | Boonsaner et al. (2011) |
| Polychlorinated biphenyls | *Medicago sativa* | Xu et al. (2010) |
| Radionuclides, Petroleum and heavy metals (Pb, As, Zn, Cd) | *Viola baoshanensis*, *Helianthus annus*, Alfalfa, Poplar, Indian mustard, cabbage | Zhuang et al. (2007) |

**5.1 MICROBIAL REMEDIATION**

Microbial bioremediation is a method for removing, degrading and immobilizing pollutants that involves microbes such as bacteria, fungi and archaea. Soil microbes degrade or immobilize metals and organic pollutants into end product using metabolism for cell growth (Verma and Kuila 2019). Therefore, microbes are essential component of remediation process for both aerobic and anaerobic decomposition. Due to their ability to thrive in a variety of environmental circumstances, microorganisms are best suited to be used in the treatment of polluted soils using a variety of ways such as biodegradation, biosorption, bio mineralization, bioaccumulation and biotransformation (Fig.1).



**Fig 1. Remediation mechanism by microorganisms in soil**

**5.1.1 BIODEGRADATION**

Microbial biodegradation occurs under aerobic or anaerobic circumstances. While various enzymes are involved in each situation, it appears that both aerobic and anaerobic microbial degradation should take place if mineralization is anticipated to occur.Pesticide biodegradation means incorporation of efficient microbial enzyme to break down the residue of pesticide into low molecular product. Various microbial diversity and their communities have a great ability to reduce pesticide persistency as eco-friendly. The anti-catabolic plasmid of microorganisms contains the pesticide-degrading gene, which encodes the contaminant-degrading enzymes. For example, *lin* gene ofgram-negative soil bacteria inscribe the specific enzyme such as dehydrogenase, dehalogenase, and hydrolase which degrade the hexachlorocyclohexane (Pan et al. 2012).

**5.1.2 BIOTRANSFORMATION**

Biotransformation is not degradation process but it transforms the toxic pollutants into other form which is less toxic or degradable by other microbial communities. It involves conversion of heavy metals, plastics and hydrocarbons to either a less toxic compound or a water-soluble state due to altered physic-chemical properties by soil microorganisms during bioremediation (Emenike et al. 2018). The heavy metals cannot be destroyed but can only be precipitated, leached, chelated, and methylated. To make the metals less poisonous, water-soluble, and perceptible, it is crucial to modify their redox state and convert them from organic to inorganic forms. In an oxidizing environment, microorganisms assist in the oxidation of the heavy metal, and nitrates and sulfates serve as terminal electron acceptors. The oxidation of organic contaminants proceeds more quickly due to the increased availability of the metals. Therefore, metal serve as terminal electron acceptor is known as dissimilatory metal reduction. For example, many bacterial and fungal communities transformed Cr (VI) to Cr (III) and Hg (II) into volatile Hg (0) which is soluble and less poisonous for the ecosystem (Hansda et al. 2016).

**5.1.3 BIOADSORPTION**

Bioadsorption is metabolism independent mechanism in which different heavy metals are absorbed by microorganism in their extracellular structures without any energy being used. Bioadsorption includes various mechanisms such as ion exchange, complexation, electrostatic interaction, diffusion, chelation, surface adsorption, and micro-precipitation which assist during effective bioremediation (Yang et al. 2015). This mechanism happens in the cell wall which has extracellular polymeric substance having acid-base properties. The cell walls, which are mostly made of lipids, polysaccharides, and proteins, provide various functional groups, such as amine, hydroxyl, phosphate, carbonyl, thiol, and sulfate groups. These compounds absorb pollutants through electrostatic, proton exchange, or micro-precipitation of heavy metals. For example, *Cunnighamellaelegans*and *Saccharomyces cerevisiae* were shown as bio-adsorbent and eliminate Cd and Zn through ion exchange process (Fang et al. 2010).

**5.1.4 BIOMINERALIZATION**

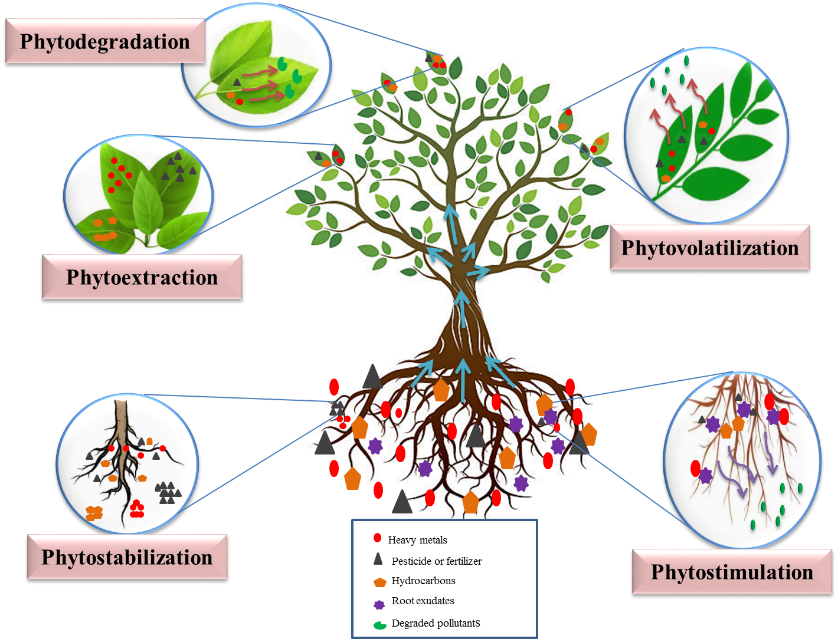
The process of converting ionic metals into solid minerals in cells and particular tissues while being influenced or controlled by biological organic matter is known as biomineralization. Depending on how much the product is regulated by biology, this mechanism can be classified into two groups (1) biologically induced mineralization which takes place outside of the cell, and (2) biologically controlled mineralization whichinvolves two ways. Cations are first actively carried within the cell, where they are subsequently dispersed throughout the organic matrix. Second, cations accumulate in the cell to form vesicles, which are subsequently transferred outside of the cell where they disintegrate in the organic matrix to liberate cations and produce minerals. Many microbial communities play a significant role in the mineralization of heavy metals from polluted area. For example, In addition to being intensively researched for their ability to immobilize Pb ions, phosphorus solubilizing bacteria (PSB) are also capable of degrading organic phosphorus and releasing enzymes such as phosphatase and phytase. These released substances by PSB could enhance the mineralization of insoluble phosphate and increase the quick formation of lead phosphate in Pb-contaminated soil (Zhu et al. 2019).

**5.1.5 BIOACCUMULATION**

Bioaccumulation is the metabolic process of microorganisms that accumulates pollutants inside the cell (Ayangbenro and Babalola 2017). Bioaccumulation includes active and passive process which is dependent on chemical, physical and biological activity for removal of pollutants. When a substance's concentration in the biosphere is significantly higher than in its surroundings, bioaccumulation occurs. Pollutants can affect the biota through the process of bioaccumulation. The lipophilic element of the cell membrane easily absorbs lipophilic pesticides using the octanol and water ratio parameters in cell metabolism. Microbial cells accumulate contaminants inthe cytoplasm in the form of insoluble products and by-products (Ojuederie and Babalola 2017). Meanwhile, soil pollutants (organic pollutants and heavy metals) significantly influence the bioaccumulation process. Furthermore, the coexistence of organic contaminants and heavy metals has a significant impact on bioaccumulation.

**5.2 PLANT-BASED REMEDIATION: PHYTOREMEDIATION**

Phytoremediation is a plant-based remediation process that is an eco-friendly and cost-effective *in-situ* mechanism which involves rhizosphere associated microbes to remove, transfer, and stabilize the contaminants. Plants can significantly contributeto cleaning organic and inorganic pollutants as well as radionuclides using various mechanisms such as phytodegradation, phytoextraction, phytostabilization, phytovolatilization, and phytostimulation(Alkorta et al. 2004) (Fig.2).

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**Fig 2. Remediation mechanism by plants in soil**

**5.2.1 PHYTODEGRADATION AND PHYTOTRANSFORMATION**

Phytodegradation is the transformation of contaminants to less toxic, immobile, and more stable forms using the plant enzyme. Phytodegradation activity does not include only microbial enzyme but also include the plants enzyme such as nitroreductase, laccase, dehalogenase, nitrilase and peroxidase. For example, plant *Canna indicaLinn*. increase phosphatase enzyme activity which promote degradation of triazophos in rhizosphere (Cheng et al. 2007). Sometimes, organic pollutants are absorbed by roots through the stimulation process and degraded by dehalogenases and oxygenase enzyme activity inside the plants. A transgenic plant using an enzyme from bacteria that hydrolyzes organophosphorus destroyed more than 99 percent of the chemical methyl parathion after 14 days of growth (Wang et al 2008).

**5.2.2 PHYTOEXTRACTION**

Phytoextraction is the process through which pollutants are taken up by plant roots, transported through the soil, and then accumulated in plant tissues. The main purpose of phytoextraction is to accumulate or store large quantities of pollutants from soil in plants that can be disposed of. The pollutants are translocated by plants on two way; (1) Air to plants and (2) soil to plants (Singh and Singh 2017). In the air-to-plant system, heavy metal-containment particles are accumulated on plant surfaces, while, foliar-applied pesticide are absorbed by leaves and deposited on leave surface. For example, Gjorgieva et al. (2011) reported that some heavy metals such as Cd, Zn, Mn, Pb Ni and Cu were accumulated on foliar plant part of *Robinia pseudoacacia, Urtica dioica* and*Matricaria recutita* growing in the industrial field. In soil to plant system, the root systems absorb pollutants close to the root surface and mostly transmit them through the xylem vessels into the shoots and leaves. The bioaccumulation factor (bioconcentration factor) of the root depicts the capacities of phytoextraction pollutants and the translocation factor of the root system represents the translocation abilities in contaminated soil (Mercado-Borrayo et al. 2015).

**5.2.3 PHYTOSTABILIZATION**

Phytostabilization is a stabilizing procedure that uses vegetation to minimize bioavailability or prevent the migration of contaminants in contaminated areas. The phytostabilization focuses on decreasing the movement and availability of contaminants, thus restricting their entry and leaching into groundwater and food systems, respectively (Khalid et al. 2017). Generally, plants containing fibrous root systems such as grasses, wetland species, and many herbaceous plants are preferred for stabilization of soil pollutants. For example, the plants*Cecropia hololeucaMiq.* and *Cecropia hololeucaMiq.* have the capacity for reducing the bioavailability of atrazine in pesticide-contaminatedfields. Pereira et al. (2013) found that *Cordia africana* plant prevented the movement of some heavy metals such as Cd, Pb, and Zn using the phytostabilization process in contaminated soil.

**5.2.4 PHYTOVOLATILIZATION**

Plants have great capability for conversion of original pollutants into volatile compounds which is released from plant body into atmosphere through transpiration, is known as phytovolatilization. Sometimes plants evaporate the pollutants in the volatile form directly through foliage and stem activity and indirectly from soil due to root activity (Limmer and Burken 2016). Contaminants are absorbed and translocated by plants by direct phytovolatilization that is more logical idea for understanding of phytoremediation. When root activities enhance the flux of volatile pollutants underground, this is known as indirect phytovolatilization. Pollutants that are easily converted into vapor and discharged into the atmosphere, such as volatile and semivolatile organic chemicals and some heavy metals, are subject to phytovolatilization. For example, pesticide trichloroethylene can be eliminated by volatilizing from the trunk of a poplar tree, leaves (0.34 ± 0.16 Kg/year), and soil-driven by root activity (0.48 ± 0.36 kg/year) (Doucette et al. 2013). Similarly, many pollutants can be removed through phytovolatilization such as heavy metals e.g. Hg, As, and Se, and pesticides e.g. carbon tetrachloride, methyl-tert-butyl ether, ethylenedibromide(Niti et al. 2013).

**5.2.5 PHYTOSTIMULATION**

Phytoremediation is the performance of plants to alter the rhizosphere's properties through rhizodeposition stimulating the rhizomicrobial community to break down toxic pollutants into less toxic compounds. Phytostimulationplaysan important role in the mineralization of heavy metals e.g. Cu, Pb, Zn, Cd, As (Imperator et al. 2019), herbicides e.g. trifloxysulfuron-sodium (Santos et al. 2010), sulfentrazone(Belo et al. 2011) and hydrocarbon (Hoffma and Yarrow 2003). Various root exudates such as carbohydrates, protein, amino acids and organic acid are released by plant root for increasing the soil microbial population and their activity which have the ability to degrade toxic compounds. Plant roots can stimulate rhizomicrobiome in different pathways(Song et al. 2019); (i) plant root offers attachment of rhizomicrobiome on the surface as residency for proliferation. (ii) Plant roots enhance the potential of microbial function by releasing the root exudate and facilitating the nutrient dynamics in the rhizosphere. (iii) Root exudates change the properties of pollutants in the rhizosphere.

**6. CURRENT CHALLENGES IN BIOREMEDIATION**

Even though bioremediation has been applied successfully to treat contaminated sites, several issues sometimes arise that make the approach less advantageous. This results in various technology-related drawbacks and the necessity for more research, both of which impose several restrictions or limitations.

**6.1 INCOMPLETE DEGRADATION**

There is uncertainty regarding the amount to which a successful degradation process can occur because the idea of a complete transformation into nontoxic compounds is simply a theoretical probability (Das and Chandran 2011). Many factors play an important role in the breakdown of pollutants such as quantities and nature of pollutants. One illustration would be the fact that the daughter product's toxicity ended up being higher as compared to parent compound, demonstrating that the method of changing a compound into a safe compound is not always certain.

**6.2 BIOLOGICAL SYSTEMS ARE HIGHLY SPECIFIC**

Environmental elements have a crucial role in influencing the success of plant and microbial activity because plants or microbes are very condition-specific when performing a process, whether it is in connection to growth circumstances or degrading activity (Das and Chandran 2011). The environment, provided nutrient quality and quantity are extremely significant in observing the process after conditioning the place of interest. In practice, it may be challenging to maintain consistency when conditions differ from one contaminated site to another due to a variety of complicated existing ecosystems. Furthermore, even under perfect circumstances, the organisms are required to metabolize the supplied nutrients to contact with the relevant pollutant. Nutrient addition may have been mainly to enhance microbial growth under favorable conditions.

**6.3 INTRODUCTION OF NON-NATIVE ORGANISMS**

Although the introduction of non-native species may have been done with the best of intentions to clean up the contaminated area, questions remain about whether the organisms do not present a hazard to other native creatures that are already present in the ecosystem. As more research is needed to understand the long-term impacts of the biodegradation process

**6.4 TECHNOLOGY STILL IN ITS INFANCY**

Although bioremediation has been successfully used on a variety of projects, it is still relatively new as a strategy for treating pollutants. Numerous studies need to be conducted to better understand the situation and build a sound theoretical foundation that will enable the advancement of current technology as well as the continued development of fresh approaches to increase efficiency and the scope of applications. Presently, there are many troubles onto generalizing a benchmark and pilot studies with regard to large scale operation (Kostka et al. 2011).

**6.5 NOT ALL POLLUTANTS ARE BIODEGRADABLE**

Only biodegradable pollutants are degraded by microbes but not all contaminants are degradable such as highly aromatic hydrocarbon and chlorinated organic compounds are unaffected by microbial degradation. Therefore, sometimes microbial remediation process may take more time as compared to other methods (Zeyaullah et al. 2009).

**6.6 TOXIC INTERMEDIATES DURING BIOREMEDIATION**

The presence of native species and a high pollution concentration could both hinder the growth of inoculated microbes (Cycon et al. 2017). Sometimes toxic intermediates are released during the breakdown of HCN and lindane which inhibit the remediation capacity of inoculated microbes as well as some native microbial population growth.

**7. FUTURE PROSPECT**

* Many findings have been reported under controlled conditions in the lab. The experimental parameters should apply under field conditions, including pollutant and weather conditions. Further research should be conducted to verify the efficiency of bioremediation in natural conditions, using alternative pot experiments. Field application of any bioremediation process should be tested at multiple locations. It is necessary to screen naturally occurring highly efficient new microbes for practical application.
* In the process of bioremediation, it's important to not only focus on specific pollutants such as heavy metals, organic pollutants, and hydrocarbons, but also consider their metabolites. The byproducts of pollutants are often more toxic than the original pollutants and can persist in the soil for a long time.
* Plants for papermaking, phytomining, bioenergy, and wood processing should be managed for harvest and post-harvest. Harvesting waste material from plant biomass must not affect the natural ecosystem.
* It is important to have the right materials, infrastructure, and tools for experiments. In order to obtain accurate results, all the materials and tools should work properly at a high level of success after being used in a contaminated site. It's important to note that if the technology is not relatively advanced, a lack of specialized advanced instruments can ultimately hinder the ability to develop and conduct research on bioremediation processes.
* It is essential to consider the intricate interaction of two or more contaminants during phytoremediation and microbial-based remediation. Their interaction could be beneficial for degrading complex pollutants. In addition, it is important to focus on understanding the interaction between plants, microbes, and the interactions between different plants and different microbes in contaminated soil conditions.

**8. CONCLUSION**

It is imperative to conduct future studies and research to develop effective bioremediation techniques that are both environmentally friendly and socially acceptable. This is crucial for removing emerging pollutants and their toxic intermediate compounds, which continue to present significant challenges to ecosystems, natural resources, and human health. It is necessary to focus on isolating, culturing, and studying naturally occurring microbes and plants with unique metabolic pathways that enable their survival in polluted areas, as this holds great promise for bioremediation efforts.

Considering the current state of bioremediation, this paper emphasizes that various factors, such as the remediation mechanisms of plants and microbes, their activity, pollutant concentration, as well as the category and characteristics of pollutants, play crucial roles in efficient and eco-friendly bioremediation. Furthermore, the implementation of multidisciplinary strategies can enhance the predictability of removing pollutants from different environments. It is also important to prioritize the development and utilization of cutting-edge technologies for monitoring, preventing, and mitigating environmental and health concerns. Identifying future challenges is essential for minimizing the environmental impacts associated with emerging contaminants.

**DECLARATION OF INTERESTS**

* The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.
* The authors declare the following financial interest or relationship that may be considered potential competing interests.

**DATA AVAILABILITY STATEMENT**

No datasets were generated or analysed during the current study.

**DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Author(s) hereby declares that no generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

**COMPETING INTERESTS**

Authors have declared that no competing interests exist

**REFERENCES**

Adams GO, Fufeyin PT, Okoro SE, Ehinomen I (2015) Bioremediation, Biostimulation and Bioaugmention: A Review**.**International Journal of Environmental Bioremediation & Biodegradation3(1):28-39. https://doi.org/[10.12691/ijebb-3-1-5](http://dx.doi.org/10.12691/ijebb-3-1-5)

Agarry S, Latinwo GK (2015) Biodegradation of diesel oil in soil and its enhancement by application of Bioventing and amendment with brewery waste effluents as Biostimulation-Bioaugmentation agents. Journal of Ecological Engineering16:82-91. https://doi.org/[10.12911/22998993/1861](https://doi.org/10.12911/22998993/1861)

Alkorta I, Hernandez-Allica J, Becerril JM, Amezaga I, Albizu I Garbisu C (2004) Recent fndings on the phytoremediation of soils contaminated with environmentally toxic heavy metals and metalloids such as zinc, cadmium, lead, and arsenic. Review of Environmental. Science and Biotechnology 3:71–90.  <https://doi.org/10.1023/B:RESB.0000040059.70899.3d>

Aranda E, Ullrich R, Hofrichter M (2010) Conversion of polycyclic aromatic hydrocarbons, methyl naphthalenes and dibenzofuran by two fungal peroxygenases. Biodegradation 21:267–281. https://doi.org/10.1007/s10532-009-9299-2

ATSDR. Priority list of hazardous (2015) Available.  <http://www.atsdr.cdc.gov/spl/index.html#modalIdString_myTable2015>

Auta HS, Emenike CU, Fauziah SH (2017) Distribution and importance of microplastics in the marine environment: a review of the sources, fate, effects, and potential solutions. [Environment International](https://www.sciencedirect.com/journal/environment-international) 102:165-176. <https://doi.org/10.1016/j.envint.2017.02.013>

Ayangbenro SA, Babalola OO (2017) A new strategy for heavy metals polluted environments: a review of microbial biosorbents*.* International Journal of Environmental Research Publication Health 14(1):94.  <https://doi.org/10.3390/ijerph14010094>

Bani A, Pavlova D, Echevarria G, Mullaj A, Reeves RD, Morel JL, Sulce S (2010) Nickel hyperaccumulation by the species of Alyssum and Thlaspi (Brassicaceae) from the ultramafic soils of the Balkans. Botanica Serbica 34(1):3-14 https://www.researchgate.net/publication/230794211\_Nickel\_hyperaccumulation\_by\_the\_species\_of\_Alyssum\_and\_Thlaspi\_Brassicaceae\_from\_the\_ultramafic\_soils\_of\_the\_Balkans

Battaglia ML, Ketterings QM, Godwin G, Czymmek KJ (2021) Conservation tillage is compatible with manure injection in corn silage system. Agronomy journal 113(3):2900-2912.  <https://doi.org/10.1002/agj2.20604>

Belo AF, Coelho A, Ferreira LR, Silva AA, Santos JB (2011) Potential of plant species in the remediation of soil contaminated with sulfentrazone. Planta Daninha 29(4):821-828. <https://doi.org/10.1590/S0100-83582011000400012>

Boonsaner M, Borrirukwisitsak S, Boonsaner A (2011) Phytoremediation of BTEX contaminated soil by *Canna generalis*. Ecotoxicology and Environmental Safety 74(6):1700-1707. <https://doi.org/10.1016/j.ecoenv.2011.04.011>

Brahney J, Hallerud M, Heim E, Hahnenberger M, Sukumaran S (2020) Plastic rain in protected areas of the United States. Science368(6496):1257-1260. <https://doi.org/10.1126/science.aaz581>

Chehregani A, Malayeri BE (2007) Removal of heavy metals by native accumulator plants. International Journal of Agriculture Biology 9(3):462-465 https://www.researchgate.net/publication/234075893\_Removal\_of\_Heavy\_Metals\_by\_Native\_Accumulator\_Plants

Cheng M, Zeng G, Huang D (2016) Hydroxyl radicals based advanced oxidation processes (AOPs) for remediation of soils contaminated with organic compounds: a review. Chemical Eng J 284:582–598. <https://doi.org/10.1016/j.cej.2015.09.001>

Cheng S, Xiao J, Xiao H, Zhang L, Wu Z (2007) Technical note phytoremediation of triazophos by Canna indica Linn. in a hydroponic system. Inter4national Journal of Phytoremediation 9:453-463. <https://doi.org/10.1080/15226510701709531>

Close ME, Humphries B, Northcott G (2021) Outcome of the first combined national survey of pesticide and emerging organic contaminants (EOCs) in ground water in New Zealand. Science of Total Environment 754:142005. <https://doi.org/10.1016/j.scitotenv.2020.142005>

Cycon M, Mrozik A, Piotrowska-Seget Z (2017) Bioaugmentation as a strategy for the remediation of pesticide-polluted soil: A review. [Chemosphere](https://www.sciencedirect.com/journal/chemosphere)[172](https://www.sciencedirect.com/journal/chemosphere/vol/172/suppl/C):52-71. <https://doi.org/10.1016/j.chemosphere.2016.12.129>

Das N, Chandran P (2011) Microbial Degradation of Petroleum Hydrocarbon Contaminants: An Overview. Biotechnology Research Interntional 13. <https://doi.org/10.4061/2011/941810>

Dong ZY, Huang WH, Xing DF (2013) Remediation of soil co-contaminated with petroleum and heavy metals by the integration of electrokinetics and biostimulation. Journal of Hazardous Material 260:399-408. <https://doi.org/10.1016/j.jhazmat.2013.05.003>

Doucette W, Klein H, Chard J, Dupont R, Plaehn W, Bugbee B (2013) Volatilization of Trichloroethylene from Trees and Soil: Measurement and Scaling Approaches. Environmental Science and Technology47(11):5813-5820. https://doi.org/[10.1021/es304115c](https://doi.org/10.1021/es304115c)

El-Borai AM, Eltayeb KM, Mostafa AR, El-Assar SA (2016) Biodegradation of Industrial Oil-Polluted Wastewater in Egypt by Bacterial Consortium Immobilized in Different Types of Carriers*.*Pol J Environ Stud 25:1901-1909. <https://doi.org/10.15244/pjoes/62301>

Emami S, Pourbabaee AA, Alikhani HA (2012) Bioremediation Principles and Techniques on Petroleum Hydrocarbon Contaminated Soil. Technical Journal of Engineering and Applied Sciences 2:320-323. <http://tjeas.com/wp-content/uploads/2012/12/320-323.pdf>

Emenike CU, Jayanthi B, Agamuthu P, Fauziah SH (2018) Biotransformation and removal of heavy metals: a review of phytoremediation and microbial remediation assessment on contaminated soil. Environmental Review 26:156-168. <https://doi.org/10.1139/er-2017-0045>

Erika AW, Vivian B, Claudia C, Jorge FG (2013) Biodegradation of phenol in static cultures by *Penicillium chrysogenumer* k1: catalytic abilities and residual phytotoxicity*.*Rev Argent Mcrobiol 44: 113-121.

Essabri AMA, Aydinlik NP, Willia NE (2019) Bioaugmentation and biostimulation of total petroleum hydrocarbon degradation in a petroleum-contaminated soil with fungi isolated from olive oil effluent. Water, Air, and Soil Pollution 230:1-16.   
https://doi.org/10.1007/s11270-019-4127-8

Fang L, Huang Q, Wei X, Liang W, Rong X, Chen W Cai P (2010) Microcalorimetric and potentiometric titration studies on the adsorption of copper by extracellular polymeric substances (EPS), minerals and their composites. Bioresource Technology. 101:5774-5779. <https://doi.org/10.1016/j.biortech.2010.02.075>

## Feng NX, Yu J, Zhao HM, Cheng YT, Mo CH, Cai QY, Li Y.W., Li H, Wong MH (2017) Efficient phytoremediation of organic contaminants in soils using plant-endophyte partnerships. Science of the total environment 583:352-368. <https://doi.org/10.1016/j.scitotenv.2017.01.075>

Fenner K, Canonica S, Wackett LP, Elsner M (2013) Evaluating Pesticide Degradation in the Environment: Blind Spots and Emerging Opportunities, Science 341:752-758. https://doi.org/[10.1126/science.1236281](https://doi.org/10.1126/science.1236281)

Gjorgieva D. Kadifkova-Panovska T, Baceva K, Stafilov T (2011) Assessment of heavy metal pollution in Republic of Macedonia using a plant assay. Archive of Environmental Contamination and Toxicology. 60:233-240.  <https://doi.org/10.1007/s00244-010-9543-0>

Hansda A, Kumar V, Anshumali A (2016) Comparative review towards potential of microbial cells for heavy metal removal with emphasis on biosorption and bioaccumulation, World Journal of Microbiology and Biotechnology 32:170. <https://doi.org/10.1007/s11274-016-2117-1>

Hesham A, Khan S, Tao Y, Li D, Zhang Y (2012) Biodegradation of high molecular weight PAHs using isolated yeast mixtures: application of metagenomic methods for community structure analyses. Environ Sci Pollut Res Int 19:3568-3578. https://doi.org/10.1007/s11356-012-0919-8

Hidayat A, Tachibana S (2012) Biodegradation of aliphatic hydrocarbon in three types of crude oil by *Fusarium* sp. F092 under stress with artificial sea water. Journal of Environmental Science and Technology 5:64-73. https://doi.org/[10.3923/jest.2012.64.73](https://doi.org/10.3923/jest.2012.64.73)

Hoang SA, Lamb D, Seshadri B, Sarkar B, Choppala G, Kirkham MB, Bolan NS (2021) Rhizoremediation as a green technology for the remediation of petroleum hydrocarbon-contaminated soils. [Journal of Hazardous Materials](https://www.sciencedirect.com/journal/journal-of-hazardous-materials) 401:123282. <https://doi.org/10.1016/j.jhazmat.2020.123282>

Hoffman KM., Nelson YM (2003) Phytostimulation of hydrocarbon biodegradation by arroyo willows in laboratory microcosms. In Phytoremediation of Petroleum-contaminated Sites-Seventh International Conference on *In Situ* and On-Site Bioremediation (Orlando FL; June 2003). Battelle Press. ISBN 1-57477-139-6.

<https://doi.org/10.1016/S1001-0742(13)60417-9>

## Huang H, Yu N, Wang L, Gupta DK, Z. He, K. Wang, Z. Zhu, X. Yan, T. Li, X.E. Yang (2011) The phytoremediation potential of bioenergy crop *Ricinus communis* for DDTs and cadmium co-contaminated soil. Bioresource Technology102:11034-11038. <https://doi.org/10.1016/j.biortech.2011.09.067>

Ibrahim SI, Abdel LMF, Khalifa HMS, Abdel MAE (2013) Phytoremediation of atrazine-contaminated soil using Zea mays (maize). Annals of Agricultural Sciences 58(1):69-75. <https://doi.org/10.1016/j.aoas.2013.01.010>

Imperato V, Portillo-Estrada M, McAmmond BM (2019) Genomic diversity of two hydrocarbon-degrading and plant growth-promoting pseudomonas species isolated from the oil field of Bobrka (Poland). Genes (Basel) 10(6):443.  <https://doi.org/10.3390/genes10060443>

## Jacob JM, Karthik C, Saratale RG, Kumar SS, Prabakar D, Kadirvelu K (2018) Biological approaches to tackle heavy metal pollution: a survey of literature. Journal of Environmental. Management217:56-70. <https://doi.org/10.1016/j.jenvman.2018.03.077>

Jin J, Sun K, Wu F (2014) Single-solute and bi-solute sorption of phenanthrene and dibutyl phthalate by plant- and manure-derived biochars. Science of the Total Environment 473-474:308-316. <https://doi.org/10.1016/j.scitotenv.2013.12.033>

Kalve S, Sarangi BK, Pandey RA, Chakrabarti T (2011) Arsenic and chromium hyperaccumulation by an ecotype of Pteris vittata-prospective for phytoextraction from contaminated water and soil. Current Science 100(6):888-894. https://www.researchgate.net/publication/264597590\_Arsenic\_and\_chromium\_hyperaccumulation\_by\_an\_ecotype\_of\_Pteris\_vittata\_\_prospective\_for\_phytoextraction\_from\_contaminated\_water\_and\_soil

Kehinde FO, Isaac SA (2016) Effectiveness of augmented consortia of Bacillus coagulans, Citrobacter koseri and Serratia ficaria in the degradation of diesel polluted soil supplemented with pig dung. Afr J Microbiol Res 10:1637-1644. <https://doi.org/10.5897/AJMR2016.8249>

Khalid S, Shahid M, Niazi NK, Murtaza B, Bibi I, Dumat C (2017) A comparison of technologies for remediation of heavy metal contaminated soils. Journal of Geochemical Explore 182:247-268. <https://doi.org/10.1016/j.gexplo.2016.11.021>

Kostka JE, Prakash OM, Overholt WA, Green SJ, Freyer G, Canion A, Delgardio J, Norton N, Hazen TC, Huettel M (2011) Hydrocarbon-Degrading Bacteria and the Bacterial Community Response in Gulf of Mexico Beach Sands Impacted by the Deepwater Horizon Oil Spill. Applied and Environmental Microbiology 77:7962–7974. <https://doi.org/10.1128/AEM.05402-11>

Kumar M, Xiong X, He M, Tsang DC, Gupta J, Khan E, Harrad S, Hou D, Ok YS, Bolan NS (2020) Micro-plastics as pollutants in agricultural soils. Environmental Pollution 265:114980. <https://doi.org/10.1016/j.envpol.2020.114980>

Kumar M, Chen HY, Sarsaiya S, Qin SY, Liu HM, Awasthi MK, Kumar S, Singh L, Zhang ZQ, Bolan NS, Pandey A, Varjani S, Taherzadeh MJ (2021) Current research trends on micro- and nano-plastics as an emerging threat to global environment: a review. Journal of Hazardous Materials409:124967. <https://doi.org/10.1016/j.jhazmat.2020.124967>

## Li CH, Wong YS, Tam NF 2010 (2010) Anaerobic biodegradation of polycyclic aromatic hydrocarbons with amendment of iron (III) in mangrove sediment slurry. Bioresource Technology101(23):8083-8092. <https://doi.org/10.1016/j.biortech.2010.06.005>

Li Z, Xiao HP, Cheng SP, Zhang LP, Xie XL, Wu ZB (2014) A comparison on the phytoremediation ability of triazophos by different macrophytes. Journal of Environmental Sciences 26(2):315-322.

Limmer M, Burken J (2016) Phytovolatilization of Organic Contaminants. Environmental Science and Technology 50:6632-6643. https://doi.org/10.1021/acs.est.5b04113

Liu Q, Tang J, Liu X, Song B, Zhen M, Ashbolt NJ (2019) Vertical response of microbial community and degrading genes to petroleum hydrocarbon contamination in saline alkaline soil. Journal of Environmental Sciences 81:80-92. <https://doi.org/10.1016/j.jes.2019.02.001>

Mercado-Borrayo BM, Cram Heydrich S, Rosas Pérez I, Hernandez Quiroz M, Ponce De Leon Hill (2015) Organophosphorus and Organochlorine Pesticides Bioaccumulation by Eichhornia crassipes in Irrigation Canals in an Urban Agricultural System. International Journal of Phytoremediation 17(7):701-708. <https://doi.org/10.1080/15226514.2014.964841>

Mohamed AT, Hussein AA-EI, Siddig MA-EI, Osman AG (2011) Degradation of oxyfluorfen herbicide by Soil microorganisms: Biodegradation of herbicides. Biotechnol 10:274-279. https://doi.org/[10.3923/biotech.2011.274.279](http://dx.doi.org/10.3923/biotech.2011.274.279)

Monica P, Darwin RO, Manjunatha B, Zuniga JJ, Diego R, Bryan RB, Mulla SI, Maddela NR (2016) Evaluation of various pesticides-degrading pure bacterial cultures isolated from pesticide-contaminated soils in Ecuador. African Journal of Biotechnology. 15(40):2224-33. https://doi.org/[10.5897/AJB2016.15418](https://doi.org/10.5897/AJB2016.15418)

Newman LA, Reynolds CM (2004) Phytodegradation of organic compounds. Curr OpinBiotechnol 15(3):225–230. <https://doi.org/10.1016/j.copbio.2004.04.006>

Niti, C., Sunita, S., Kamlesh, K., & Rakesh, K. (2013). Bioremediation: An emerging technology for remediation of pesticides. Research Journal of Chemistry and Environment 17(4).

Niu GL, Zhang JJ, Zhao S, Liu H, Boon N (2009) Bioaugmentation of a 4- chloronitrobenzene contaminated soil with Pseudomonas putida ZWL73. Environmental Pollution57(3):763-771. <https://doi.org/10.1016/j.envpol.2008.11.024>

Ojuederie OB, Babalola OO (2017) Microbial and Plant-Assisted Bioremediation of Heavy Metal Polluted Environments: A Review. International Journal of Environmental Research Publication Health 14(12):1504.  <https://doi.org/10.3390/ijerph14121504>

Pan LW, Siegrist RL, M Crimi (2012) Effects of *In Situ* Remediation Using Oxidants or Surfactants on Subsurface Organic Matter and Sorption of Trichloroethene. Groundwater Monitaring and. Remediation 32:96-105.  <https://doi.org/10.1111/j.1745-6592.2011.01377.x>

Paranthaman SR, Karthikeyan B (2015) Bioremediation of heavy metal in paper mill effluent using *Pseudomonas*spp. International Journal of Microbiology 1: 1-5. https://microbiozjournals.com/bioremediation-of-heavy-metal-in-paper-mill-effluent-using-pseudomonas-spp

Pereira ACC, N.M.B.D.A. Sobrinho NMBDA, Tolon-Becerra A, Magalhaes MOL, Lastra-Bravo X (2013) Use of Cordia Africana in the Phytostabilization of Substrates from Excavations of the Ore Courtyard at the Port of Itaguai. Brazil, Soil & Sediment Contamination 22(4):376-389. https://doi.org/10.1080/15320383.2013.733446

Pereira P, Enguita FJ, Ferreira J, Leitao A (2014)DNA damage induced by hydroquinone can be prevented by fungal detoxification. [Toxicology Reports](https://www.sciencedirect.com/science/journal/22147500) 1:1096-1105**.** <https://doi.org/10.1016/j.toxrep.2014.10.024>

Priyalaxmi R, Murugan A, Raja P, Raj KD (2014) Bioremediation of cadmium by *Bacillus safensis* (JX126862), a marine bacterium isolated from mangrove sediments. International Journal of Current Microbiology and Applied Sciences 3:326-335.

Pure Earth. The new top six toxic threats: a priority list for remediation, world’s worst pollution problems report (2015) Available. <http://www.worstpolluted.org/docs/WWPP_2015_Final.pdf>

Rahman Z, Singh VP (2019) The relative impact of toxic heavy metals (THMs) (arsenic (As), cadmium (Cd), chromium (Cr)(VI), mercury (Hg), and lead (Pb)) on the total environment: an overview. Environmental. Monitaring and Assessment 191(7):419. <https://doi.org/10.1007/s10661-019-7528-7>

## Rajendran, P, Gunasekaran, P (2019) Microbial bioremediation. MJP Publisher.

Ravi RK, Pathak B, Fulekar MH (2015) Bioremediation of Persistent Pesticides in Rice field Soil Environment Using Surface Soil Treatment Reactor. Int J Curr Microbiol App Sci 4:359-369.

Ricardo IA, Alberto EA, Junior AHS, Macuvele DLP, Padoin N, Soares C, Riella HG, Starling MCVM, Trovo AG (2021) A critical review on micro-plastics, interaction with organic and inorganic pollutants, impacts and effectiveness of advanced oxidation processes applied for their removal from aqueous matrices. Chemical Engineering Journal 424:130282. <https://doi.org/10.1016/j.cej.2021.130282>

Santos EA, Costa MD, Ferreira LR, Reis MR, Franca AC, Santos JB (2010) Atividaderizosferica de solo tratado com herbicidaduranteprocesso de remediacaopor*Stizolobium aterrimum*. Pesquisa Agropecuaria Tropical 40(1):1-7. https://doi.org/[10.5216/PAT.V40I1.4670](https://doi.org/10.5216/PAT.V40I1.4670)

Seleiman MF, Almutairi KF, Alotaibi M, Shami A, Alhammad BA, Battaglia ML (2021) Nano fertilizer as an emerging fertilization technique: why modern agriculture can benefit from its use? Plants 10(1):2.  <https://doi.org/10.3390/plants10010002>

Sharma B, Dangi AK, Shukla P (2018) Contemporary enzyme based technologies for bioremediation: a review. Journal of Environmental Management 210:10-22. <https://doi.org/10.1016/j.jenvman.2017.12.075>

Simarro R, Gonzalez N, Bautista LF, Molina MC (2013) Assessment of the efficiency of in situ bioremediation techniques in a creosote polluted soil: change in bacterial community*.*J Hazard Mater 262:158-167. <https://doi.org/10.1016/j.jhazmat.2013.08.025>

Singh A, Kumar V, Srivastava JN (2013) Assessment of Bioremediation of Oil and Phenol Contents in Refinery Waste Water via Bacterial Consortium. J Pet Environ Biotechnol 4:1-4. https://doi.org/10.4172/2157-7463.1000145

Singh T, Singh DK (2017) Phytoremediation of organochlorine pesticides: Concept, method, and recent developments. International Journal of Phytoremediation 19:834-843. <https://doi.org/10.1080/15226514.2017.1290579>

Sinha SN, Biswas M, Paul D, Rahaman S (2011) Biodegradation potential of bacterial isolates from tannery effluent with special reference to hexavalent chromium. Biotechnology Bioinformatics and Bioengineering 1:381-386. https://doi.org/10.6084/m9.figshare.1279416.v1

Sinha SN, Paul D (2014) Heavy metal tolerance and accumulation by bacterial strains isolated from waste water. Journal of Chemical, Biological and Physical Sciences 4: 812-817. https://www.researchgate.net/publication/259681437\_Heavy\_Metal\_Tolerance\_and\_Accumulation\_by\_Bacterial\_Strains\_Isolated\_from\_Waste\_Water

Sivaram AK, Logeshwaran P, Lockington R, Naidu R, Megharaj M (2018) Impact of plant photosystems in the remediation of benzo [a] pyrene and pyrene spiked soils. Chemosphere 193:625-634. <https://doi.org/10.1016/j.chemosphere.2017.11.081>

Song B, Xu P, Chen M, Tang W, Zeng G, Gong J, Zhang P, Ye S (2019) Using nanomaterials to facilitate the phytoremediation of contaminated soil. Critical. Review in Environmental Science and Technology49(9):791-824. <https://doi.org/10.1080/10643389.2018.1558891>

Song C, Jingwei Z, Gengdong H, Shunlong M, Liming F, Yao Z, Jiazhang C, Xiaowei Z (2019) Risk assessment of chlorantraniliprole pesticide use in rice-crab coculture systems in the basin of the lower reaches of the Yangtze River in China. [Chemosphere](https://www.sciencedirect.com/journal/chemosphere) 230:440-448. <https://doi.org/10.1016/j.chemosphere.2019.05.097>

Subramanian M, Oliver DJ, Shanks JV (2006) TNT phytotransformation pathway characteristics in Arabidopsis: role of aromatic hydroxylamines. Biotech. Progress 22(1):208–216. <https://doi.org/10.1021/bp050241g>

Sukumar S, Nirmala P (2016) Screening of diesel oil degrading bacteria from petroleum hydrocarbon contaminated soil*.* Int J Adv Res Biol Sci 3:18-22. Link: <https://goo.gl/PAoc9z>

Tang J, Zhang J, Ren L, Zhou Y, Gao J, Luo L, Yang Y, Peng Q, Huang H, Chen A (2019) Diagnosis of soil contamination using microbiological indices: A review on heavy metal pollution. Journal of Environmental Management 242:121-130. <https://doi.org/10.1016/j.jenvman.2019.04.061>

Thavamani P, Megharaj M, Naidu R (2015) Metal-tolerant PAH-degrading bacteria: development of suitable test medium and effect of cadmium and its availability on PAH biodegradation. Environmental Science and Pollution Research 22:8957-8968. https://doi.org/10.1007/s11356-013-1850-3

Tsaboula A, Menexes G, Papadakis EN, Vryzas Z, Kotopoulou A, Kintzikoglou K, Mourkidou EP (2019) Assessment and management of pesticide pollution at a river basin level part II: Optimization of pesticide monitoring networks on surface aquatic ecosystems by data analysis methods. [Science of The Total Envir](https://www.sciencedirect.com/journal/science-of-the-total-environment)onmental[653](https://www.sciencedirect.com/journal/science-of-the-total-environment/vol/653/suppl/C):1612-1622. <https://doi.org/10.1016/j.scitotenv.2018.08.240>

Verma JP, Jaiswal DK, Sagar R (2014) Pesticide relevance and their microbial degradation: a-state-of-art, Review in Environmental Science and Biotechnology 13:429-466. https://doi.org/10.1007/s11157-014-9341-7

Verma S, Kuila A (2019) Bioremediation of heavy metals by microbial process. Environmental Technology and Innovation14:100369. <https://doi.org/10.1016/j.eti.2019.100369>

Wang X, Wu N, Guo J, Chu X, Tian J, Yao B, Fan Y (2008) Phytodegradation of organophosphorus compounds by transgenic plants expressing a bacterial organophosphorus hydrolase. Biochemical and biophysical research communications 365(3):453-458. <https://doi.org/10.1016/j.bbrc.2007.10.193>

Xu L, Teng Y, Li ZG, Norton JM, Luo YM (2010) Enhanced removal of polychlorinated biphenyls from alfalfa rhizosphere soil in a field study: the impact of a rhizobial inoculum. Science of the Total Environment 408(5):1007-1013. <https://doi.org/10.1016/j.scitotenv.2009.11.031>

Yang T, Chen ML, Wang JH (2015) Genetic and chemical modification of cells for selective separation and analysis of heavy metals of biological or environmental significance, TrAC-Trends in. Analytical Chemistry 66:90-102. <https://doi.org/10.1016/j.trac.2014.11.016>

Zeng G, Chen M, Zeng Z (2013) Risks of neonicotinoid pesticides. Science 340:1403. https://doi.org/10.1126/science.340.6139.1403-a

Zeyaullah MD, Atif M, Islam B, Abdelkafe AS, Sultan P, ElSaady MA, Ali A (2009) Bioremediation: A tool for environmental cleaning. Affrican Journal of Microbiology Research.3(6):310-314. https://www.researchgate.net/publication/237500789\_Bioremediation\_A\_tool\_for\_environmental\_cleaning

## Zhang M, Wang J, Bai SH, Zhang Y, Teng Y, Xu Z (2019) Assisted phytoremediation of a co-contaminated soil with biochar amendment\_ Contaminant removals and bacterial community properties. Geoderma 348:115-123. <https://doi.org/10.1016/j.geoderma.2019.04.031>

Zheng F, Zhu D, Giles M, Daniell T, Neilson R, Zhu YG, Yang XR (2019) Mineral and organic fertilization alters the microbiome of a soil nematode Dorylaimusstagnalis and its resistome. Science of Total. Environmental 680:70-78. <https://doi.org/10.1016/j.scitotenv.2019.04.384>

Zhu X, Lv B, Shang X, Wang J, Li M, Yu X (2019) The immobilization effects on Pb, Cd and Cu by the inoculation of organic phosphorus-degrading bacteria (OPDB) with rapeseed dregs in acidic soil. Geoderma 350:1-10. <https://doi.org/10.1016/j.geoderma.2019.04.015>

Zhu ZQ, Yang XE, Wang K (2012) Bioremediation of Cd-DDT co-contaminated soil using the Cd-hyperaccumulator Sedum alfredii and DDT-degrading microbes. Journal of Hazardous Materials 235-236:144–151. <https://doi.org/10.1016/j.jhazmat.2012.07.033>

Zhuang P, Yang QW, Wang HB, Shu WS (2007) Phytoextraction of heavy metals by eight plant species in the feld. Water Air Soil Pollut 184(1-4):235-242.  https://doi.org/10.1007/s11270-007-9412-2