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Remediation of Environmental Contaminants Through Phytotechnology

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Abstract Environmental pollution caused by organic pollutants, radionuclides, and potentially toxic elements (PTEs) affects the quality of the biosphere (water, air, and soil). Rapid industrial growth, mining, agricultural inputs, sewage water, and industrial effluents application in soil all contribute to contamination. Remediation of these valuable resources, as well as prevention of new pollutants, have long been required to avoid negative health effects. Several remediation strategies have been applied for environmental pollutants. Phytoremediation is potentially a viable and promising approach which uses green plants to remove, detoxify, or degrade toxic PTEs from the environment. In this review, the application of phytotechnology for pollutants removal and their underlying mechanisms (phytoextraction/phytoaccumulation, phytotransformation, phytostimulation, phytovolatilization, phytorhizodegration, and phytostabilization) were studied. The current study pointed out that the efficiency of phytoremediation can be affected by various factors such as treatment time, temperature, pH, EC, OM, plant density, electric field, and chelating agents. In the end, this review systematically summarized existing knowledge, merits/demerits, prospects, and future aspects of the phytoremediation for remediating polluted soil and water bodies.

Keywords Pollutants removal · Phytoremediation mechansims · Factors · Merits and demerits · Prospects · Future recommendations

Highlights

- For environmental pollutants cleaning from contaminated sites, phytoremediation is a viable and ecologically friendly technique.
- Various plants could be employed in phytoremediation to lower the pollutants.
- Plant species use distinct phytomechanisms to phytoremediate various contaminants.
- The efficiency of phytoremediation is affected by various factors.
- Future prospects and merits/demerits of phytoremediation are supported by recent research.

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1 Introduction

The unprecedented industrial growth and urbanization has expedited economic growth while simultaneously destroying the soil ecosystems, particularly the challenge of potentially toxic elements (PTEs) and polycyclic aromatic hydrocarbons (PHCs) pollution in soil. They are very toxic, persistants in nature, and easily accumulated in body which threaten ecosystems and human health by entering in to food chain, causing widespread concern around the world (Yadav et al., 2018; Gan et al., 2022). Soil PTEs are mostly sourced from both natural and man-made sources such as mining, smelting and processing, automotive emissions, and oil well extracting operations, agricultural inputs, sewage water, and industrial effluents are the main sources of PTEs (Kafle et al., 2022). PAHs are a group of organic compounds that have two or more linked benzene rings, and the US-EPA (Environmental Protection Agency) has recognized 16 of them as priority pollutants due to their oncogenic, mutagenic, and teratogenic properties. Increased PAH levels in the environment, as well as their ecotoxicity and human health effect, have sparked several studies into removing them from the environment.

Remediation approaches include biological, chemical, and physical methods. Generally, physical and chemical remediation procedures for the removal of PTEs/organic contaminants (OPs) are commonly used. Although these approaches are considered appropriate for removing PTEs/OPs from the environmental sites, but they are expensive and difficult to apply and can change the soil properties (Selvi et al., 2019). In this regard, phytoremediation is a biotechnological solution for the degradation or removal of organic and inorganic pollutants from soil, as they are feasible, cheap, and accessible option (Gavrilescu, 2022). Plant creates a huge quantity of biomass and develops quickly in order to build a vegetation cover in a given location on time, and roots play key role in preserving soil structure, and preventing soil erosion (Yan et al., 2020). With the comparison, previous methods of active cleanup or removal of pollutants, phytoremediation is low maintenance, cost effective, and more appealingly process of remediating contaminated sites such as soil (Liu et al., 2011; Zhou et al., 2005). Although plants can reduce some OPs concentrations, this process is frequently too inefficient to be of practical use. The introduction of genes known to be involved in pollutants metabolism in many organisms can considerably improve the viability of phytoremediation (Doty, 2008; Sharma et al., 2022; Van Aken, 2008).

Phytotechnologies rely on the basic physiological processes of higher plants and allied microbes, such as photosynthesis, mineral feeding, transpiration, and metabolism. Plants extend their roots in water, sediments, and soil, and absorb inorganic and organic compounds; roots can balance and fix substances on their outer surfaces while interacting with microbial species (Marmiroli et al., 2006). Various mechanisms involved in phytoremediation process are phytoextraction, phytostabilization, phytoevaporation, rhizofiltration, and rhizodegradation (Mahar et al., 2016). In this

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technology, plants are used to clean up pollutants in the environment, including metals, pesticides, explosives, oil, and organic pollutants (Etim, 2012). The phytoremediation potential of some of the plants against the environmental pollutants is presented in Table S1.

Although many reviews have been published on the application of phytoremediation of specific pollutants (heavy metals, polycyclic hydrocarbons, or dyes) (Yadav et al., 2018; Agarwal et al., 2019; Cui et al., 2021; Kafle et al., 2022; Oladoye et al., 2022; Gavrilescu, 2022), but there is no comorehensive study regarding the phytoremediation of PTEs, OPs, pharmaceutical, dyes, and other PTEs, exploring the involved mechanisms, explaining the factors affecting the phytoremediation process for targeted contaminants, and discussing merits/demerits and future aspects of phytoremediation technology.

2 Phytoremediation of Pollutants

2.1 Phytoremediation of PTEs

The harmful effects of PTEs on the environment are now obvious and well documented. It affects plant growth microbial processes and ultimately has a detrimental impact on soil fertility. Consequently, it increases the importance of remediation ways to lower the concentration of PTEs from the environment (Yan et al., 2020). In recent times, a study shows silver grass (*Miscanthus floridulus*) has great possibility as a phytoremediation crop to extract PTEs from soil (Wu et al., 2022). In another study, Cr and Cu were removed by the silver grass (Shrestha et al., 2019). Similar results are reported by Zhang et al., (2021), where Cd was extracted by oilseed rape crop. Various plant species used for the remediation of PTEs are presented in Table 1.

2.2 Phytoremediation of Organic Pollutants

The OPs have received significant attention due to their persistence, toxicity, carcinogenicity, and harmfulness to human health even at lower concentrations. They are released into the environment through agricultural activities (fertilizers, herbicides, pesticides), chemical industry, leakage (solvents, petroleum), military activities (chemical weapons, explosives), urbanization, and wood processing (Nwoko, 2010. The OPs of specific concern consist of hydrocarbons, polycyclic aromatic hydrocarbons, chlorinated biphenyls chlorophenols, toluene, phenols, and benzene, polybrominated diphenyl ethers (PBDEs), halo-hydrocarbon, and polycyclic aromatic hydrocarbons (PAHs), etc. (Diez, 2010; Ren et al., 2018). Organic compounds enter organisms through eating contaminated food or direct contact with contaminated places. As a result, one of the primary concerns in the areas of environmental science and engineering is the removal of toxic chemicals from water and soil to ensure better preservation of human health and the environment (da Conceição Gomes et al., 2016). Physicochemical methods for the reduction of organic compounds are expensive, laborious, and environmentally destructive approaches (Azubuike et al., 2016).

Table 1 Phytoremediation of PTEs

Sr. no.	Plant species	PTEs	References
1	Amaranthus hypochondriacus L	Cd	(Cui et al., 2021)
2	Festuca arundinacea	Cd	(Zhang et al., 2022)
3	Phyllanthus amarus and Cyanodon dactylon	As, Zn, Cr, and Cu	(Singh et al., 2022)
4	Trifolium alexandrinum L.	Cd, Cr, Cu, Ni, Pb, and Zn	(Pescatore et al., 2022)
5	Gomphrena claussenii	Zn and Cd	(Ferreira et al., 2022)
6	Eichhornia crassipes, Xanthium strumarium L., Cynodon dactylon, Croton bonplandianum Baill)	Cr	(Hasan et al., 2021)
7	Lolium perenne	Cd	(Xie et al., 2021)
8	Brassica napus L	Cd	(Rao et al., 2019)
9	Cyrtomiumma crophyllum	Hg	(Xun et al., 2017)
10	Alyssum bertolonii	Ni	(Mengoni et al., 2011)

Phytoremediation methods use green plants, such as herbs (*Thlaspi caerulescens*, *Brassica juncea*, *Helianthus annuus*) and woody (e.g., *Salix* spp. *Populus* spp) plants, which absorb and remove organic compounds and other radioactive compounds from water or soil (Hussain et al., 2021). Plants absorb and then metabolize (phytotransformation, phytodegradation), or plant-assisted microbial degradation to remove OPs from the soil. Plant roots also immobilize certain OPs for example polycyclic aromatic hydrocarbons (Reichenauer & Germida, 2008). Table 2 shows various plant species used for the remediation of OPs.

2.3 Phytoremediation of Dyes

Dyes are synthetic organic compounds that dissolve well in water and are subdivided into reactive, alkaline, and acidic. When the color is provided to the substrate during the dyeing process, the crystal structure of the colored substance is changed. Dyes are a vital part of daily life and are used in the textile and fiber industries (Gaballah et al., 2021), plastic industries, automobile manufacturing plants, rubber industries, and paper industries (Sharma et al., 2021). Today, the textile industry is the fastest growing industry, generating $1 trillion, accounting for 7% of the world's total exports, and directly or indirectly involving 35 million workers worldwide (Desore & Narula, 2018). Over 7×10^5 tons of synthetic dyes and 10,000 structurally different colors are produced each year to meet the demands of changing fashion trends (Chequer et al., 2013). Unfortunately, due to the inefficiency of the dyeing process, more than 200,000 tons of dyes are lost during dyeing and finishing, and this wastewater ends up in bodies of water (Ogugbue et al., 2011). Regardless of the undeniable importance of the textile industry, it is one of the world's largest sources of pollution. Most textile dyes are carcinogenic, toxic, and mutagenic. They are severely toxic and can irritate the skin and eyes, runny nose, and occupational asthma, severe damage to the liver, kidneys, reproductive system, nausea, bleeding, central nervous system, and brain (Ramachandran & Gnanadoss, 2013). Untreated wastewater pollutes water bodies and can increase turbidity and temperature, impart unpleasant odors, and change pH and color. These properties not only prevent light from penetrating water but also reduce photosynthetic activity (Lellis et al., 2019). Dyes are harmful to the soil's microbiological ecosystems, reduce seed germination, and inhibit the absorption of nutrients and plant growth, which ultimately leads to a decrease in yield (Rehman et al., 2018).

In the past, various physical (ion exchange filtration, adsorption, and oxidation) and chemical approaches such as ozonation and coagulation have been used to treat wastewater contaminated with dyes, but they are expensive and time-consuming. Recently, the use of natural resources such as bioremediation and phytoremediation has become increasingly popular due to low-cost and environmentally

Table 2 Phytoremediation of organic pollutants

Sr. No.	Plant	Organic pollutants	References
1	Typha spp	Clofibric acid	(Dordio et al., 2009)
2	Lupinus luteus	BTEX compounds	(Taghavi et al., 2011)
3	Medicago sativa	Polycyclic aromatic hydrocarbon	(Xiao et al., 2015)
4	Eichhornia crassipes	Organic pollutants	(Rezania et al., 2015)
5	Lolium, Trifolium repens, and Apium graveolens	PAH-contaminated soils over monocultures	(Meng et al., 2011)
6	Solanum lycopersicum	DDT-polluted soils	(Mitton et al., 2014)
7	Fatsia japonica and Ficus benjamina	Volatile organic compounds	(Kim et al., 2008)
8	Arbuscular mycorrhiza	Polycyclic aromatic hydrocarbons	(Joner & Leyval, 2003)
9	Petunia atkinsiana	Benzene and toluene pollutants	(Zhang et al., 2011)
10	Nicotiana tabacum	Polychlorinated biphenyls	(Novakova et al., 2009)
11	Solanum lycopers cum	Phenol	(González et al., 2006)
12	*Pontederia crassipes*	Sodium dodecyl sulfate	(Gong et al., 2018)

friendly approaches (Ekanayake & Manage, 2020). The different groups of plants that have the remediating potential of the most effective dyes are highlighted in Table 3.

2.4 Phytoremediation of Pharmaceuticals

Pharmaceuticals are a broad group of natural or synthetic biologically active ingredients used for the treatment and prevention of human and veterinary diseases. Medicines and personal care products are recognized as emerging environmental problems. After ingestion, the active ingredients are partially converted and discharged from the body into the sewage system as a mixture of metabolites and biologically active forms. Large amounts of waste are generated during the production of medicines from the industry (Patneedi & Prasadu, 2015). Wastewater is discharged into water bodies, and wastewater is used directly as irrigation water in dry areas and water-scarce areas. Similarly, the biosolids produced by waste treatment plants are used as arable land amendments or fertilizers (Du & Liu, 2012). Antibiotics, preservatives, analgesics, anti-hypertensive drugs, anti-inflammatory drugs, hormones, contraceptives, anti-epileptics, cancer treatment drugs, lipid-lowering drugs, cosmetic ingredients, beta-blockers, and other personal care products and other medicine products are considered to be micro-pollutants in the environment (Shakeel et al., 2020). Veterinary antibiotic debris in animal urine and manure is a source of agricultural land amendment and contributes to environmental pollution (Nguyen et al., 2021). In underdeveloped countries, pharmaceutical waste and its effluent are discharged into soil and water without any treatment, thereby deteriorating water quality and affecting aquatic life, plant growth, and animal health. The pharmaceutical waste contained a variety of organic compounds that were carcinogenic and toxic to human and animal health (Hussain et al., 2021).

In agricultural soils, plants take up pharmaceutical compounds via their roots and accumulate in different parts of the plant, which inhibits seed germination and destroys the photosynthetic apparatus, which in turn leads to a

Table 3 Phytoremediation of dyes

Sr. no.	Plant	Dyes	References
1	Zinnia angustifolia	Sulfonated diazo	(Khandare et al., 2011)
2	Blumea malcolmii	Sulfonated azo dye	(Kagalkar et al., 2009)
3	Pontederia crassipes	Red RB and black B	(Muthunarayanan et al., 2011)
4	Vigna radiata and Leucaena leucocephala	Textile dye	(Jayanthy et al., 2014)
5	Pontederia crassipes	Azo dye	(Davies et al., 2005)
6	Glandularia pulchella	Textile effluent and mixture of structurally different dyes	(Kabra et al., 2012)
7	Portulaca grandiflora	Sulfonated diazo reactive dye navy blue HE2R (Reactive Blue 172)	(Khandare et al., 2011)
8	Alternanthera philoxeroides	Sulfonated remazol red dye	(Rane et al., 2015)
9	Glandularia pulchella	Sulphonated azo dye Green HE4B	(Kabra et al., 2011)
10	Petunia grandiflora Juss	Disulfonated triphenylmethane textile dye Brilliant blue G	(Watharkar et al., 2013)
11	Petunia Grandiflora and Gailardia grandiflora	Textile dye	(Watharkar & Jadhav, 2014)
12	Sesuvium portulacastrum	Textile dye, reactive green 19A-HE4BD	(Lokhande et al., 2015)
13	Lagerstroemia speciosa	Dye degradation	(Saraswathi et al., 2017)
14	Hydrocotyle vulgaris	Textile dye	(Vafaei et al., 2013)
15	Chara vulgaris	Congo red dye	(Mahajan & Kaushal, 2014)
16	Tagetes erecta, Aster amellus, Portulaca grandiflora and Portulaca grandiflora	Dyes from textile wastewater	(Chandanshive et al., 2018)
17	Cactaceae	Textile dye degradation	(Adki et al., 2012)
28	Azolla pinnata	Malachite green	(Kooh et al., 2016)

reduction in the yield of sugar peas, rice, and cucumbers and other vegetables. Hence, removing pharmaceuticals from the environment is the top concern of environmentalists (Li, 2014). The drugs can be eliminated by physical processes such as adsorption or volatilization, biodegradation, or chemical reactions such as ozone treatment (Boxall et al., 2004). Recent studies conducted on pharmaceuticals removal through phtotechnology are highlighted in Table 4.

2.5 Phytoremediation of Radionuclides

There has been a surge of interest in recent years in the pollution caused by industrial plants handling materials containing high levels of natural radionuclides (NOR). The most prominent nuclear accidents, in 1986 in Ukraine (Chernobyl) and in 2011 in Japan (Fukushima), discharged massive amounts of radionuclides into the atmosphere in the form of gases, volatiles, and refractory elements. Furthermore, nuclear waste leaks and nuclear weapon testing from nuclear plants, and agricultural and medical testing facilities using isotopes as tracer agents all contribute to radioactive contamination (Yan et al., 2021). Mining and ore processing can increase NOR products, byproducts, and wastes in the environment and at plant sites. The most polluting industries are uranium mining and processing, mining and metallurgical industry, and phosphate industry. The levels of radionuclides in products and/or wastes from the oil and gas industry and from the production of rare earth elements, zirconium and ceramics, and radioactive cesium may be especially high, but waste streams are limited (Vandenhove, 2000; Vandenhove et al., 2002). The radionuclide plant extraction approach is quite new. In addition, most of the experiments conducted to test the radionuclide phytoremediation approach were performed on hydroponic cultivation systems (Tomé et al., 2008). Saleh (2012) concluded that water hyacinth (*Eichhornia crassipes*) recovered 97% 60Co and up to 90% 137Cs after 24 h of contact. Paulo et al., (2006) used the species *Callitriche stagnalis Scop*., *Potamogeton natans* L., and *Potamogeton pectinatus* L. The authors tested uranium removal in closed channels. The work of this system was very efficient. The concentration of uranium in water dropped from 500 to 220 μg/L in 24 h, and after 2 weeks, it dropped to 72.3 mg/L (Paulo et al., 2006).

2.6 Phytoremediation of Air Pollutants

Globally, air pollution is a serious health hazard, particularly for middle- and low-income countries. There are a variety of evidences that air pollution can negatively affect human health, including chronic obstructive pulmonary disease (COPD), acute respiratory infections (ARIs), lung cancer, and increased mortality (Banerjee et al., 2017). Although industrial combustion technology and emission control systems have the potential to minimize pollution, there is still a pressing need to discover alternative, environmentally beneficial, and long-term solutions to the problem of rising air pollution. Phytoremediation is a technique for treating soil and water pollutants that helps to reduce pollution in the environment (Agarwal et al., 2019). Phytoremediation, on the other hand, has been investigated for its ability to clean ambient air through the plant's gas-exchange mechanism with ambient air. Gaseous pollutants can be adsorbed/absorbed by autotrophic plants during their life-supporting processes, which necessitate intense gas exchange. Phytoremediation is a process in which plants and its associated microbes accept contaminants from the air and degrade or detoxify them via a variety of methods (Agarwal et al., 2019), as shown in Fig. 1. This has been shown to be a successful plant-based, environmentally friendly, and long-term process for reducing air pollutants in both indoor and outdoor areas.

3 Mechanisms of Phytoremediation

Phytoremediation is the use of plants to remove, stabilize, or remediate contaminants in soil, sediment, and water bodies; and it is based on several major strategies/techniques for the remediation of pollutants, including phytoextraction, phytofiltration, phytostabilization, phytodegradation, and phytovolatilization as given in Fig. 2. The capability of a plant species to effectively restore a metal-polluted site is determined by a variety of parameters such as the quantity of metals that can be stored by the plant, the growth rate of the plant, and the planting density (Ali et al., 2013).

3.1 Phytoextraction

Phytoextraction is also referred to as phytoabsorption; phytoaccumulation or phytosequestration is the process by which plants absorb PTEs from the soil and store them in their aerial parts. In phytoextraction

Table 4 Phytoremediation of pharmaceuticals

Sr. no.	Plant species	Pharmaceutical	References
1	Typha spp.	Clofibric acid	(Dordio et al., 2009)
2	Salix exigua	Synthetic estrogen, 17α-ethynylestradiol, anti-hypertensive, diltiazem and anti-convulsant, diazepam	(Franks et al., 2006)
3	Helianthus annus L.	Tetracycline and oxytetracycline	(Gujarathi, Haney, Park, et al., 2005a)
4	Acrostichum aureum and Rhizophora apiculata Blume Fl. Javae	Fluoroquinolones (ciprofloxacin and norfloxacin)	(Hoang et al., 2013)
5	Softstem bulrush	Caffeine, naproxen, diclofenac, carbamazepine, and clofibric acid	(Zhang et al., 2013)
6	Common water hyacinth and Cyperus alternifolius	Levonorgestrel	(Li, 2014)
7	Brassica nigra	Aspirin and tetracycline	(Gahlawat & Gauba 2016)
8	Pistia stratiotes and Myriophyllum aquaticum	Tetracycline and oxytetracycline	(Gujarathi, 2005b)
9	Phragmites australis	Praziquantel	(Marsik et al., 2017)
10	Azolla caroliniana, Lemna minor, and Pistia stratiotes	Diltiazem, diphenhydramine, and sulfamethoxazole	(Maharjan, 2014)
11	*Helianthus annuus* and Zea mays	Carbamazepine and 10,11-epoxycarbamazepine	(Ryšlavá et al., 2015)
12	Cicer arietinum	Aspirin	(Gahlawat et al., 2014)
13	Typha latifolia, Phragmites, Iris germanica, and Juncus effuses	Ibuprofen and ohexol	(Zhang et al., 2016)
14	Typha latifolia, Phragmites australis, Iris pseudacorus, and Juncus effusus	Imazalil and tebuconazole	(Lv et al., 2016)
15	Lemna gibba	Lomefloxacin, sulfamethoxazole, and chlortetracycline	(Brain et al., 2004)
16	Lemna	Acetaminophen, diclofenac, progesterone, ofloxacin (OFX)	(Allam et al., 2015)
17	Chrysopogon zizanioides	Tetracycline	(Datta et al., 2013)
18	Glycine max	Carbamazepine, diphenhydramine, fluoxetine, triclosan and triclocarban	(Wu et al., 2010)
10	Chrysopogon zizanioides	Naproxen	(Marsidi et al., 2016)
20	Dracaena fragrans, Opuntia microdasys	Benzene, toluene, ethylbenzene, and xylene	(Mosaddegh et al., 2014)
21	*Phragmites australis*	Ibuprofen	(He et al., 2017)

process, PTEs are translocated onto the aerial section of plants (Zacchini et al., 2009). There are two types of phytoextraction: natural and induced phytoextraction. In the natural phytoextraction technique, only plants in their natural state are used in the soil, with no amendments. Different chelating compounds such as EDTA, elemental sulfur, citric acid, and ammonium sulfate are employed as amendments to boost the bioavailability of metals for plant absorption in induced or chelated aided phytoextration (Lai & Chen, 2004; Sun et al., 2011). When chelates are mixed with soil, they form water-soluble complexes that help remove PTEs from the soil particles. The PTEs are accessible for plant uptake at acidic pH; hence, reducing the soil pH increases their bioavailability. Secondary pollutants can result from chemical treatment. Synthetic EDTA, which is used in chelation, is non-biodegradable and may be harmful to the environment if it is leached into ground water. When present in high concentrations, these chelating compounds are hazardous

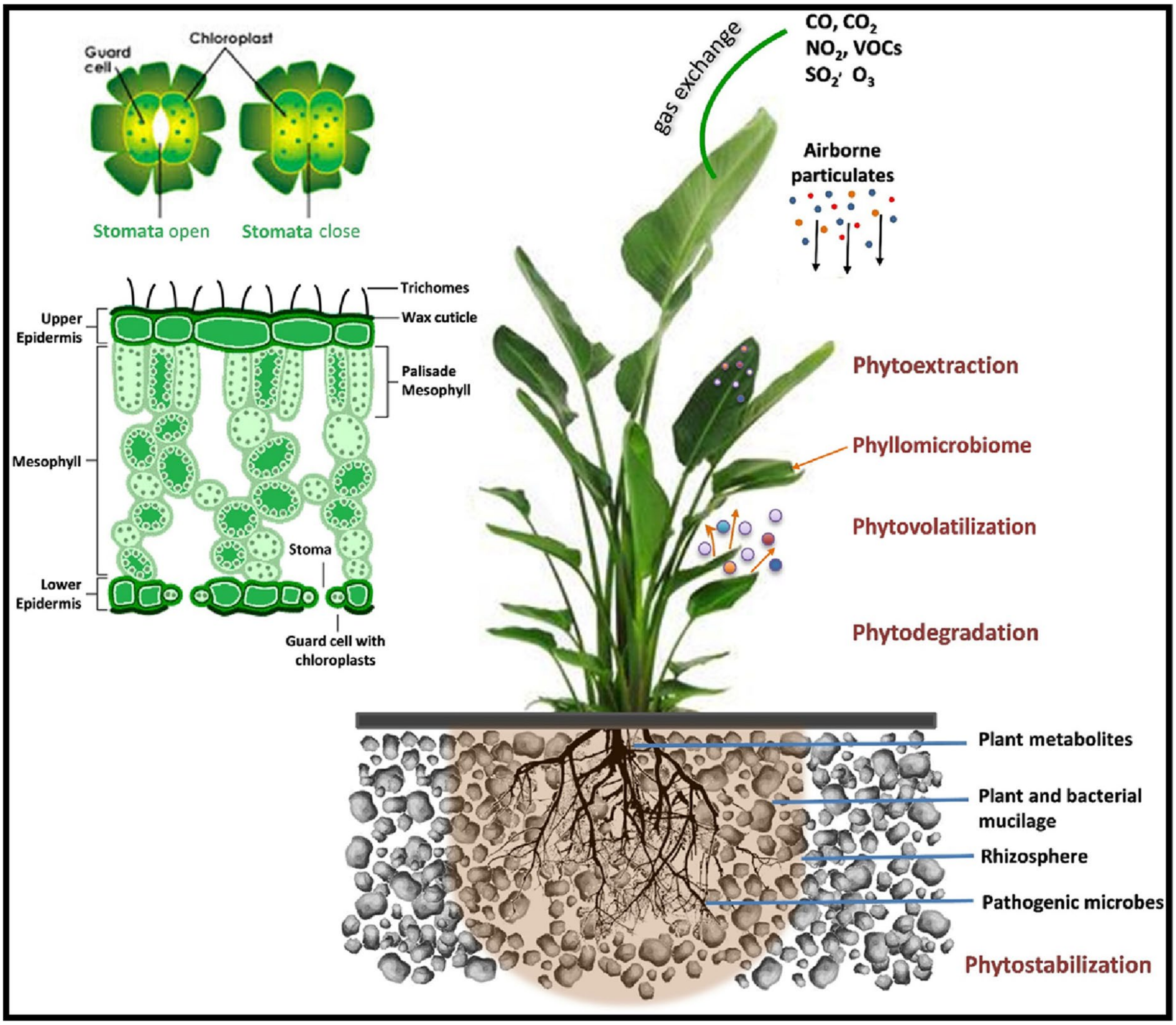

Fig. 1 Mechanism of phytoremediation by plant-soil-microbe system (Agarwal et al., 2019)

to plants (Zhao et al., 2011; Zhuang et al., 2009). Citric acid is a naturally occurring chelating agent that is non-toxic to plants, readily biodegradable, and has no effect on plant development, and it was noticed that chelation improves phytoextraction of Cu, Cd, Pb, Zn, and Ni (Smolińska & Król, 2012). Some of the exemplary studies conducted on phytoremediation of PTEs are given in Table 5.

The hyperaccumulation process in plants is a game-changer in this technology. When compared to conventional plants, these plants may absorb a larger amount of PTEs. Three key traits separate hyperaccumulators from equivalent non-hyperaccumulating taxa: a greatly enhanced rate of PTEs absorption, a quicker root-to-shoot translocation, and a stronger capacity to detoxify and sequester PTEs in leaves (Oladoye et al., 2022). Examples of specific plants used as hyperaccumulators in phytoremediation are comprehensively given in Table 6 .

3.2 Phyto Stabilization

Plants are used to stabilize pollutants in contaminated soils in a process known as phytostabilization, which is also known as phyto-immobilization, and it is used in the environment to reduce pollutant mobility and bioavailability, thereby preventing contaminants from entering the human food chain. Plants in the soil immobilize PTEs by sorption, complexation, and

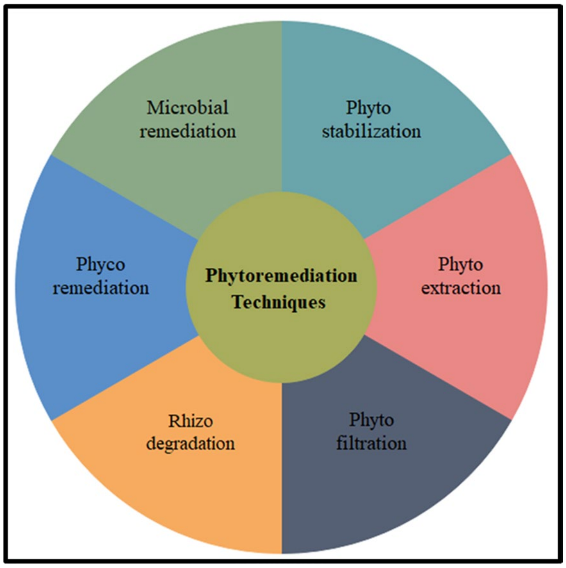

Fig. 2 Phytoremediation mechanisms involved in environmental remediation

precipitation in the rhizosphere (Gavrilescu, 2022; Yoon et al., 2006). Phytodeposition or phytosequestration refers to plant's capacity to collect certain PTEs in their leaves and root zones. Because of the binding of PTEs with organic matter, primary fixation of PTEs achieves adsorption on the surface of the roots, physical stability of soil particles, and precipitation in the root zone. The toxicity of PTEs varies with their valency. Plants convert these hazardous states into less toxic forms. Cr (VI) is converted to Cr (III), which is less toxic and has lower mobility (Gavrilescu, 2022, Wu et al., 2010).

PTEs are not permanently eliminated since their mobility is limited; therefore, they remain in the soil. In a technique known as phytostabilization, PTEs are employed to stabilize plants. Several organic and inorganic supplements are used to improve PTEs fixation via sorption and precipitation. Because pollution may occasionally prevent plants from thriving, phytostabilization is a possible strategy for large-scale remediation (Vangronsveld et al., 2007). The amendment should be low-cost, safe for workers, simple to use, and non-toxic to plants. Because of their low cost, organic amendments are employed in phytostabilization to enhance soil physical characteristics and nutritional status. The specific plants used for phytostabilization are presented in Table 7.

Phytovolatilization refers to the process through which plants absorb pollutants from the soil, transform them into volatile form, and then release them into the atmosphere. Phytovolatilization removes the majority of OPs and certain inorganic PTEs for instance, Hg and Se from the soil. It has drawbacks since it does not entirely remove toxins and raises the risk of redeposition in soil. As a result, it is a contentious technology (Padmavathiamma & Li, 2007).

3.3 Phytofiltration and Phycoremediation

Because of their low cost and environmental friendliness, phytofiltration and phycoremediation are new and gaining in popularity. In phytofiltration, aquatic plants (floating or submerged) are used to remove pollutants from waste water via their root system, whereas in phycoremediation, macro or micro algae and cyanobacteria are used for biotransformation or

Table 5 Phytoaccumulation technology used for PTEs removal

Sr. no.	Plants species	Pollutant	References
1	Mentha aquatica and Mentha longifolia	Ni	(Zurayk et al., 2002)
2	Riccinus communis	Ni	(Adhikari & Kumar, 2012)
3	Azolla species	Cr	(Arora et al., 2006)
4	Nicotiana tabacum	Cd	(Gorinova et al., 2007)
5	Lactuca sativa	Cd	(Tang et al., 2016)
6	Lemna gibba	Zn	(Khellaf & Zerdaoui, 2009)
7	Mentha aquatica and Mentha longifolia	Ni	(Zurayk et al., 2002)
8	Pontederia crassipes	As	(Giri et al., 2012)
9	*Helianthus annuus*, Nicotiana tabacum tobacco, and Chrysopogon zizanioides	Pb	(Boonyapookana et al., 2005)
10	Pontederia crassipes and Centella asiatica	Cu	(Mokhtar et al., 2011)

Table 6 Hyperaccumulator plant species used for PTEs removal

Sr. no.	Plant species	Heavy metal	Reference
1	*Helianthus annuus*	Cd and Ni	(January et al., 2008)
2	Populus and Salix	Cd	(Robinson et al., 2000)
3	Thlaspi caerulescens	Zn and Cd	(Zhao et al., 2003)
4	Solanum nigrum	Cd	(Ji et al., 2011)
5	Brassica juncea	Cd	(Qureshi et al., 2010)
6	Al	Pb	(Cho-Ruk et al., 2006)
7	Zea mays	Pb	(Hovsepyan & Greipsson, 2005)
8	Brassica juncea	Pb	(Lim et al., 2012)
9	Jatropha curcas	Hg	(Marrugo-Negrete et al., 2015)
10	Atriplex canescens, Brassica nigra and Lupinus sp.	Hg	(Moreno et al., 2004)
11	Helianthus annus L.	Cd, Cr, and Ni	(Turgut et al., 2004)
12	Ipomoea aquatica	Cr	(Chen et al., 2010)
13	Phragmites australis, Typha angustifolia L. and Cyperus esculentus	Cd, Cr, Cu, Mn, Fe, Ni, Pb and Zn	(Chandra & Yadav, 2011)
14	Lemna minor	Cu, Cr and Pb	(Üçüncü et al., 2013)
15	Arundo donax and miscanthus sacchariflorus	Zn and Cr	(Li, 2014)
16	Pistia stratiotes	Cr and Co	(Prajapati et al., 2012)
17	Berkheya coddii	Ni and Co	(Keeling et al., 2003)
18	Pennisetum purpureum, Helianthus annus L.	Cr and Co	(Lotfy & Mostafa, 2014)
19	Brassica napus	Co	(Adilouglu & others, 2016)
20	Solanum lycopersicum	Co	(Bakkaus et al., 2005)

removal of contaminants, for example, nutrients and xenobiotics from contaminated water and CO_2 from polluted air. Plant roots (rhizofiltration), seedlings (blastofiltration), and excised plant shoots (caulofiltration) can all be used to minimize subterranean water contamination (Mesjasz-Przybyłowicz et al., 2004).

3.4 Phytodegradation

Phytodegardation is the enzymatic degradation of OPs within plants. Degradation is carried out by plant-produced enzymes such as dehalogenase and oxygenase rather than rhizospheric bacteria (Vishnoi & Srivastava 2007). The organic pollutants are removed by plants, and metabolic activities clean them. Plants are known as the "Green Liver" of the biosphere. Due to the fact that PTEs are not biodegradable, they are only relevant to organic pollutants. Transgenic poplars, for instance, are genetically modified trees that are used to degrade synthetic herbicides and insecticides through phytodegradation (Dhankher et al., 2012).

3.5 Rhizodegradation and Microbial Remediation

The rhizosphere is the area under the effect of roots that extends up to 1 mm surrounding the roots. Microbial remediation, on the other hand, refers to the breakdown of organic/inorganic contaminants in rhizospheric soil using microorganisms (Mukhopadhyay & Maiti, 2010). The degradation of OPs in the rhizosphere is accelerated by increasing the number of microbes and their metabolic activity. Exudates from plant roots, such as sugars, amino acids, and flavonoids, increase microbial activity in the rhizosphere by 10–100 times. Root exudates are a source of carbon and nitrogen, providing a nutrient-rich environment for microorganisms and encouraging microbial activity. Plants also produce enzymes that help break down organic contaminants in contaminated soil (Kuiper et al., 2004).

3.6 Bacterial Endophytes in Heavy Metal Phytoremediation

Interactions between plants and microbes in rhizospheric soil promote PTEs phytoremediation efficacy

Table 7 Phytostabilization technology used for PTEs removal

Sr. no.	Plant species	Pollutants	References
1	Lupinus albus	Cd and As	(Vázquez et al., 2006)
2	Calamagrostis arundinacea	As	(Antosiewicz et al., 2008)
3	Tamarix gallica	As	(Moreno-Jiménez et al., 2009)
4	Athyrium wardii	Pb and Zn	(Zou et al., 2012)
5	Daucus carota	Pb	(Babaeian et al., 2016)
6	Athyrium wardii	Pb	(Zou et al., 2011)
7	Juncus effuses	Pb	(Najeeb et al., 2017)
8	Festuca perennis and tall fescue	Zn and Pb	(Rizzi et al., 2004)
9	Quercus	Cd	(Dominguez et al., 2009)
10	Brassica juncea, luffa cylindrica and sorghum halepense	Ni	(Rajkumar et al., 2013)
11	Solanum nigrum	Ni	(Ferraz et al., 2012)
12	Spartina densiflora brongn and Spartina maritima	Co, Cr, and Ni	(Cambrollé et al., 2011)
13	Rosa rubiginosa	Cr	(Ramana et al., 2013)
14	Pistacia lentiscus	Zn, Pb, and Hg	(Concas et al., 2015)

in polluted soil. Selected microbes are injected into plants to increase PTEs phytoremediation in contaminated soil. Plant growth-promoting rhizobacteria (PGPR) in polluted soil reduce PTEs phytotoxicity and boost biomass output, according to Dharni and co-workers (Dharni et al., 2014). The friendly ecosystem is the result of long-term co-evolution between plants and endophytic bacteria, which aids plant survival in stressful situations while also improving the natural ecological system's equilibrium (Ryan et al., 2008). Endophytic bacteria have evolved numerous ways of reducing PTEs ion toxicity in polluted soil, including hazardous form change, metal fixation on the cell surface, precipitation, and adsorption. In contaminated natural or artificial soil, the growth of plants and phytoremediation processes have been improved by introducing metal-resistant endophytic bacteria that increase cell elongation, nutrient uptake, and metal stabilization and reduce metal stress in plants (Ma et al., 2016). Microbial-assisted phytoremediation has been shown to reduce metal phytotoxicity and alter PTEs phytoavailability in contaminated soils by exhibiting endophytic bacterial traits such as metal detoxification/transformation/sequestration. Endophytic bacteria help plants survive under stressful conditions, and phytoremediation efficacy is increased by increasing plant growth, lowering metal stress and toxicity, and changing metal bioavailability in soil and to plants (Ma et al., 2015).

4 Factors Affecting Phytoremediation Process for Pollutants Removal

Phytoremediation cycles and efficiency can be influenced or limited by a variety of factors, according to a previous study. The choice of appropriate plants is critical to the efficacy of phytoremediation technology. Plant species must have a lot of biomass, a fast growth rate, and a lot of ability to absorb and accumulate PTEs, which is influenced by soil properties and microbiota, the bioavailability of PTEs, living organisms, climate, and environmental circumstances (Hauptvogl et al., 2019). The bioavailability of PTEs can directly affect the efficiency of plant extraction. Soil pH, oxygen, moisture, organic matter, and other factors can affect the bioavailability of PTEs (Zeng et al., 2017). Metals in soils are usually divided into three categories based on whether they can be eaten by plants: accessible, inaccessible, and replaceable. The metal attached to biological matter, oxide, or carbonate of Fe-Mn, which cannot be removed by plants, is the exchangeable fraction. The solubility of PTEs in the soil is mostly influenced by pH, according to many investigations. Due to limited solubility, high pH (alkalinity) might reduce metal bioavailability (Zeng et al., 2017).

4.1 Treatment Time

Phytoremediation is a unique technology that uses plants to clean up pollution from diverse ecological compartments. Single plants or mixed species are used in this technology to segregate plants or eliminate toxins from contaminated environmental compartments. The time necessary for successful phytoremediation depends entirely on the plant species involved. For instance, after more than 100 days of treatment, pyrene can be virtually eliminated, with levels as low as 15 mg/kg (Košnář et al., 2018). In other cases, longer treatment times only removed 60% of pyrene from perennially contaminated soil (García-Sánchez et al., 2018).

4.2 Temperature

When the temperature was between 25 and 42 °C, pyrene-degrading bacteria degraded pyrene more efficiently. Pyrene becomes more physiologically accessible and thus more biodegradable as the temperature rises, but it also poses a greater risk of pyrene discharge into the environment. The biological activity of pyrene degradation products can be inhibited by pH values outside the 5.0–8.0 range (Yang et al., 2021). Yang et al., (2021) found pH ranged 7.0–8.0, ideal for *Mycolicibacterium* sp. pyrene functioning, with high pyrene removal efficiency also at pH levels up to 9.0. The activity of *Mycolicibacterium* sp. Pyrene was reduced when the pH was raised above pH 10.0 or decreased below pH 5. The effect of temperature on plant per-fluoroalkyl substances (PFAS) uptake has previously been hypothesized based on the contents of four perfluorinated carboxylic acids (PFCAs) in wheat compartments under various temperatures. The results showed that around 20–30 °C, the 4 PFCA accumulated in both roots and shoots increased dramatically, presumably due to increased PFCA adsorption due to increased transpiration (Zhao et al., 2016). As a result, it is obvious that environmental conditions have a significant impact on PFAS uptake in plants. However, several putative pathways remain unknown, such as how pH affects PFAS bioaccumulation in plant compartments. As a result, a further in-depth research is required.

4.3 pH

The changes in pH can have a significant impact on PFAS bioaccumulation in plant compartments. Krippner and co-workers used pot experiments to test wheat PFAS uptake at different pH levels (5.0, 6.0, and 7.0). They found that the rate of PFCA uptake, excluding perfluorononanoic acid (PFNA) and perfluorooctanoic acid (PFDA), increased significantly as the tested pH value increased (Krippner et al., 2014). Zhao et al., (2013) found comparable results for PFOS, reporting that the greatest perfluorooctane sulfonic acid (PFOS) absorption was detected at pH = 6.0, with the tested pH value increasing from 4.0 to 10.0. Therefore, it is assumed that the measured pH value of maximum PFOS uptake is precisely within the optimal pH range (5.8–6.5) for wheat growth, thus facilitating favorable conditions for PFOS uptake and translocation in plant compartments (Zhao et al., 2013). However, the underlying mechanism of PFCA uptake at varying pH is still unknown.

According to Willscher et al. (2017), low metal concentrations and pH 5.0–6.0, full growth of *Helianthus tuberoses* was observed. At pH 5.0, the metal concentration in the shoot rose as the concentration of soil metal increased. Under acidic conditions, changing the pH of the medium considerably improved the removal efficiency. At neutral and basic circumstances, no significant variations in Cr (VI) removal efficiency were found; nevertheless, basic conditions resulted in a greater translocation factor (Masinire et al., 2021).

4.4 EC

Root absorption and PFAS translocation are both affected by salinity (Zhao et al., 2016). Increasing salinity from 0.03 to 7.25 psu increased PFOS bioaccumulation in wheat seedlings in hydroponic testing in a water-plant system, To investigate the underlying processes, wheat may have increased water intake to maintain correct osmotic pressure in the presence of increased electrolyte concentrations in the solution (Zhao et al., 2016).

4.5 OM

Dissolved organic matter (DOM), a type of water-soluble organic complexes including components of varying molecular weights, has potential practical value in soil remediation due to benefits such as broad sources (e.g., straw, farmyard manure, and trash) and low-cost utilization (Bahemmat et al., 2016). The availability of PTEs in the soil is affected differentially by DOM from diverse sources; DOM aids in the phytoremediation of PTEs-polluted soils. It was found that DOM application increased soil nutrients by increasing soil OM and accessible nutrients (AP, AK), as well as the proportion of soil Cd active fraction and decreasing the proportions of Cd residual fractions by 1–7%. Furthermore, pyrene sorption is robust and virtually rapid under high SOM conditions (Diagboya et al., 2021).

4.6 Plant Density

Plant density is a critical factor in phytoremediation. Previous research suggests that plant density can influence plant growth and quality in various ways. Nutritional availability of macrophytes may be affected by both species and plant density. Plant density had an effect on soil fibrous root reinforcement. Because of competition among plants, density has a significant influence on reproduction, biomass accumulation, and root architecture . However, nothing is known about the impact of the plant density of submerged macrophytes on the remediation of polluted sediments (Loades et al., 2010).

Initial planting density management can be used to maximize barium phytoextraction from the soil, thereby shortening the time required for soil decontamination. Remediation of polycyclic aromatic hydrocarbons (PAHs) using *Vallisneria spiralis* concluded that the density of *Vallisneria spiralis* is an important factor for remediation of polluted sediments (Liu et al., 2014).

4.7 Electric Field

The application of a low-intensity electric current (continuous or alternating) has a significant impact on remediation efficiency because toxins may be mobilized and transported to plant roots under these conditions, increasing the capacity and intensity of phytoremediation. Furthermore, as a result of improved nutritional bioavailability or the influence of electric current on enzyme activities, membrane transport, and water activity, biomass output increases (Mao et al., 2016). Previous studies proved that electric fields showed a considerable influence on ryegrass remediation of PTEs-contaminated soil. Sánchez et al., (2019) published the results of an EK-assisted phytoremediation experiment with maize and a poor permeability soil treated with atrazine (Sánchez et al., 2019). The work investigated the changes in electrochemical and biological processes that occurred in the pot's various soil portions (anode, cathode, and interelectrode region). It was the first extensive research that demonstrated the effect of an electrical field on plant growth and organic pollutant breakdown in diverse soil sections. Cang et al. (2012) evaluated the impact of direct-current (DC) electric current on plant development and PTEs speciation in soil. The study presented the results of plant metal concentrations and bioavailable soil metal concentrations in different soil sections, with an emphasis on the relationship between extractable soil metal and plant metal contents. The effect of an electrical field on the concentration of PTEs in plants varied according to plant species, HM type, and soil section. Shoot metals accumulation in the center region of both plants was enhanced by at least 20% in Cd, Cu, and Zn co-contaminated soils (except for Zn in ryegrass). Electrical fields had the most significant impact on ryegrass copper absorption, with shoot Cu accumulation increasing by 32.5% across the board (Yuan et al., 2021)

4.8 Chelating Agents

Ethylene diamine disuccinic acid (EDDS), ethylene diamine tetraacetate (EDTA), and nitrilotriacetic acid (NTA) are three commonly used chelating retailers (Tananonchai et al., 2019). They can increase the solubility of PTEs and, as a result, choose plant-based heavy metal extraction. For example, one of the most well-known complexing retailers, EDTA, has high complexing constants (log k) with PTEs such as Cu (18.8), Ni (18.5), Pb (18.0), Zn (16.4), and Cd (16.4), and its presence within the soil has a significant impact on heavy metal mobility (Chauhan et al., 2015). A study conducted by Li et al., (2020) discovered that the addition of EDTA in concentrations determined by laboratory research significantly increased the solubility of compounds containing Cd and Pb within the soil and desired the absorption of Pb, Zn, and Cd in rapeseed, corn, and wheat. The findings confirmed that the method could be used to calculate the appropriate dose of a chelating agent for phytoremediation of a radionuclide or other poisonous heavy metal-infected soil using (Li et al., 2020).

5 Merits/Demerits of Phytoremediation

- The utilization of phytoremediation has been proven as a viable approach by numerous specialists (Yadav et al., 2018; Gu et al., 2022; Shah et al., 2022; Yang et al., 2022).
- It is probably the least expensive biotechnology, which is likewise normal and "harmless to the ecosystem.
- Phytoremediation is accepted and admired by the general public.
- Such cleaning factors apply to plant species that can or have already grown generally in their respective contaminated areas, so they do not further pollute the environment.
- The simplicity of utilization and pertinence to an enormous assortment of metals, radionuclides, and natural substances
- Implementation of plant development and all physiological processes and phytoremediation mechanisms, as plants use solar energy to the extent necessary for growth in a completely natural way.
- These techniques for removing toxic metals from the soil are economically more cost-effective due to their low cost.
- This technology does not degrade the ecosystem like the implementation of other cleaning technologies.
- Phytoremediation is an attractive approach to repairing soil contaminated with PTEs, but it is subject to restrictions (Farraji et al., 2016; Adeoye et al., 2022).
- Phytoremediation takes time. I need this extended time.
- Low proficiency because of slow development and low biomass creation
- Limited bioavailability to plants as a result of firmly following with soil particles
- Highly polluted soils do not support plant growth and are therefore applicable to soils with low levels of pollutants.
- Increased risk of food chain contamination due to improper management and improper care during the repair process
- Challenge to the correct handling of plant-extracted biomass
- Volatilization of mixtures can change over a groundwater defilement issue to an air contamination issue.
- The hyperaccumulative plants frequently just amass a particular component, which demonstrates restricted materialness to locales containing various blended pollutant.
- Natural conditions can impact supportable phytoremediation.
- Soil changes and other agricultural practices can adversely affect the bioavailability of pollutants.
- There is still a lack of basic research to effectively harness the immense potential of these technologies. In this regard, the integration of new molecular tools with prior knowledge of plant genetics, physiology, and biochemistry is expected to significantly advance the understanding of the associated mechanisms of pollutant degradation.
- Climatic conditions are a restricting element.

6 Prospects

- Indeed, plant biotechnology approaches have played an important role in the development of transgenic crops with improved potential for efficient, clean, and inexpensive bioremediation technologies, and sustainability is very promising; there are still some challenges.
- Regulatory restrictions may be reevaluated frequently to make the use of transgenic plants less burdensome.
- Insufficient knowledge about the complex relationships that exist between the biosphere and the mechanisms based on the ability of plants to take up and move metals from contaminated environments.
- Plant treatment technologies must be engineered with multiple genes stacked to meet site-specific requirements.
- Developing genes suitable for plant treatment to understand better the molecular basis of the pathways involved in the breakdown of pollutants.
- Plant treatment technology has just been tested in the field for transgenic plants. Biosecurity issues need to be appropriately addressed, and strategies to prevent gene flow in wild species need to be developed.
- A collaboration between microscopic organisms or growths that can become the rhizosphere and plants may give more significant obstruction and better conditions for metal extraction by expanding their bioavailability and giving substances to working with phytoremediation.
- In contrast with the costly regular procedures, sun-powered-driven phytoremediation is biologically a superior and promising decision with a bright future.

7 Future Recommendations

- The accomplishment of phytoremediation relies likewise generally upon the capacity of plants to endure the toxins to be eliminated. It is along these lines of most extreme significance to decide the maximal conceivable measure of the xenobiotic intensifies that can be amassed and detoxified without injury, basic pressure, and disturbance of plant digestion or redox processes in the species viable.
- Future fighter mediation studies will elucidate genetic, molecular, and cellular mechanisms to understand how to improve fighter mediation, as well as genetic, molecular, biochemical, physiological, and agricultural science. May include a better understanding of whether a target level is needed (Krämer, 2005).
- PCR intensification and DNA finger impression or microarray quality chip might give more bits of knowledge on the cycle and may prompt pick a particular plant assortment or microbial strain to be applied on a particular toxin inside a built wetland or a specific soil. Since contaminations and their side effects can be harmful to people and other living life forms, including plants, an inside and out observing of phytoremediation ought to be done to know whether metabolites created or delivered are as yet poisonous.
- Limited research on natural mercury phytremediator plants (Shiyab et al., 2009) and the high toxicity of this element to humans (Harris et al., 2003).
- Future research needs to focus on plant identification, their PTEs detoxification mechanisms, signaling pathways, and their response to individual metals in order to develop sustainable phytoremediation mechanisms.
- Key challenges and increased efficiency of plant technology include dissemination of results, risk assessment, public awareness and acceptance of this green technology, as well as among scientists, industry, stakeholders, end-users, and non-governmental organizations. It depends on facilitating networking. Government agency. It is an important issue that must be addressed to ensure that the phytoremediation program is implemented successfully.
- At long last, energy crops and focused on phytomining endeavors will give cost counterbalancing and asset creating openings for a considerable length of time gatherings.
- To fully elucidate the effects of PTEs on plants, future studies will need to investigate the molecular properties of microorganisms and plants in response to pollutants. To develop a more efficient plant-microbial consortium for pollutant removal, we need a better understanding of plant-microbial interactions.
- More research is needed to investigate the effects of different types of catalysts on the efficiency of phytoremediation in order to improve the practicality of phytoremediation in environmental remediation.
- Efforts should be made to protect the environment and reduce the impact on natural resources for sustainable development, focusing on the research and use of this technology to obtain treated water that meets the standards.

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