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PHYTOREMEDIATION: ASSESSMENT OF ENVIRONMENTAL POLLUTANTS AND TRANSGENIC PLANTS

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REVIEW BASED BOOK CHAPTER

PHYTOREMEDIATION: ASSESSMENT OF ENVIRONMENTAL POLLUTANTS AND TRANSGENIC PLANTS

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Abstract

The intensification of anthropogenic activities, driven by the growing global population and the need to meet modern demands for food and goods, has led to the release of various contaminants into the environment. These contaminants, ranging from organic and inorganic chemicals to aerosols and heavy metals, pose significant environmental and health risks as they accumulate in the surroundings. In response to these challenges, various approaches and techniques are being explored to ensure environmental sustainability. One such approach is phytoremediation, which leverages the natural processes of plants to remediate pollutants. This article explores the literature on phytoremediation, detailing its mechanisms and applications in addressing different types of pollutants. Phytoremediation processes can be further enhanced through the use of symbiotic microorganisms and the introduction of genes responsible for proteins and enzymes that facilitate the uptake and detoxification of contaminants. Drawing on contemporary literature, this article examines the diverse processes of phytoremediation and its effectiveness in remedying soil and air pollution using both natural and transgenic plant species.

Keywords
Phytoremediation, Transgenic Plants, Soil Pollutants, Heavy Metals, Air Pollutants

1. Introduction

Contamination of the environment by waste products, whether from agricultural, industrial, or domestic sources, poses numerous human health and environmental risks [1, 2]. Organic contaminants, typically xenobiotic to plants, are foreign to their natural environment. Inorganic contaminants, on the other hand, consist of metals present in relatively low concentrations in the soil [3-5]. Organic molecules enter plant roots through simple diffusion, while inorganic metal contaminants utilize multiple cell membrane transporters or H+-coupled carrier proteins for uptake [6]. Plants absorb metals such as Iron (Fe), Cobalt (Co), Manganese (Mn), Molybdenum (Mo), Zinc (Zn), and Copper (Cu) as essential micronutrients. However, certain metals, known as non-essential metals, can have toxic effects on both plants and the environment, even at low concentrations. These non-essential metals, including heavy metals, are characterized by their high density, often exceeding 4-5 g/cm3, which contributes to their harmful effects [7-9].

Various forms of pollution in the environment lead to the deposition of heavy metals and other contaminants in soil, water, and air. Understanding the sources of pollution helps assess remediation processes. Heavy metals in the environment originate from parent rocks and human activities. Soil contamination occurs when man-made cycles surpass natural cycles, heavy metals become bio-available, transfer from mining activities, waste products contain high metal concentrations, or due to excessive fertilizer and pesticide use. Anthropogenic sources include mining, fertilizer and pesticide treatment, biosolids, and manures, emitting heavy metals in organic, inorganic, and elemental forms [10].

Pollution from atmospheric deposition of particulate matter (PM) stems from industrial activities involving the release of burned petroleum and coal [11, 12]. The environmental pollutants include heavy metals such as Zn, Pb, Cu, and Ni, exceeding natural levels [13] along with greenhouse gases (GHGs) [14], aerosols [15], and volatile organic particles like carbonyl, aromatic and halogenated compounds [16].

Wastewater, used for irrigation, not only increases soil conductivity and organic carbon content but also decreases soil pH [17]. Wastewater treatment plants can also release pollutants like microplastics, contaminating rivers [18] and subsequently leading to soil pollution when used for agricultural irrigation. Heavy metals accumulate primarily in the plowing layer of farmland. Soils regularly receiving wastewater sewage sludge tend to have higher concentrations of heavy metals [19, 20].

Organic and inorganic chemical pollution in soil and water is a global concern due to its adverse effects on ecosystem structure and function. Traditional methods for reclaiming contaminated lands, such as soil cleaning, electro dynamics, and toxic matrix exhumation, primarily rely on physicochemical techniques. While these methods are highly effective, they often suffer from drawbacks such as high costs and inefficiency, especially when contaminants are present in low quantities [21].

Environmental pollutants have diverse sources, as illustrated in Figure 1.

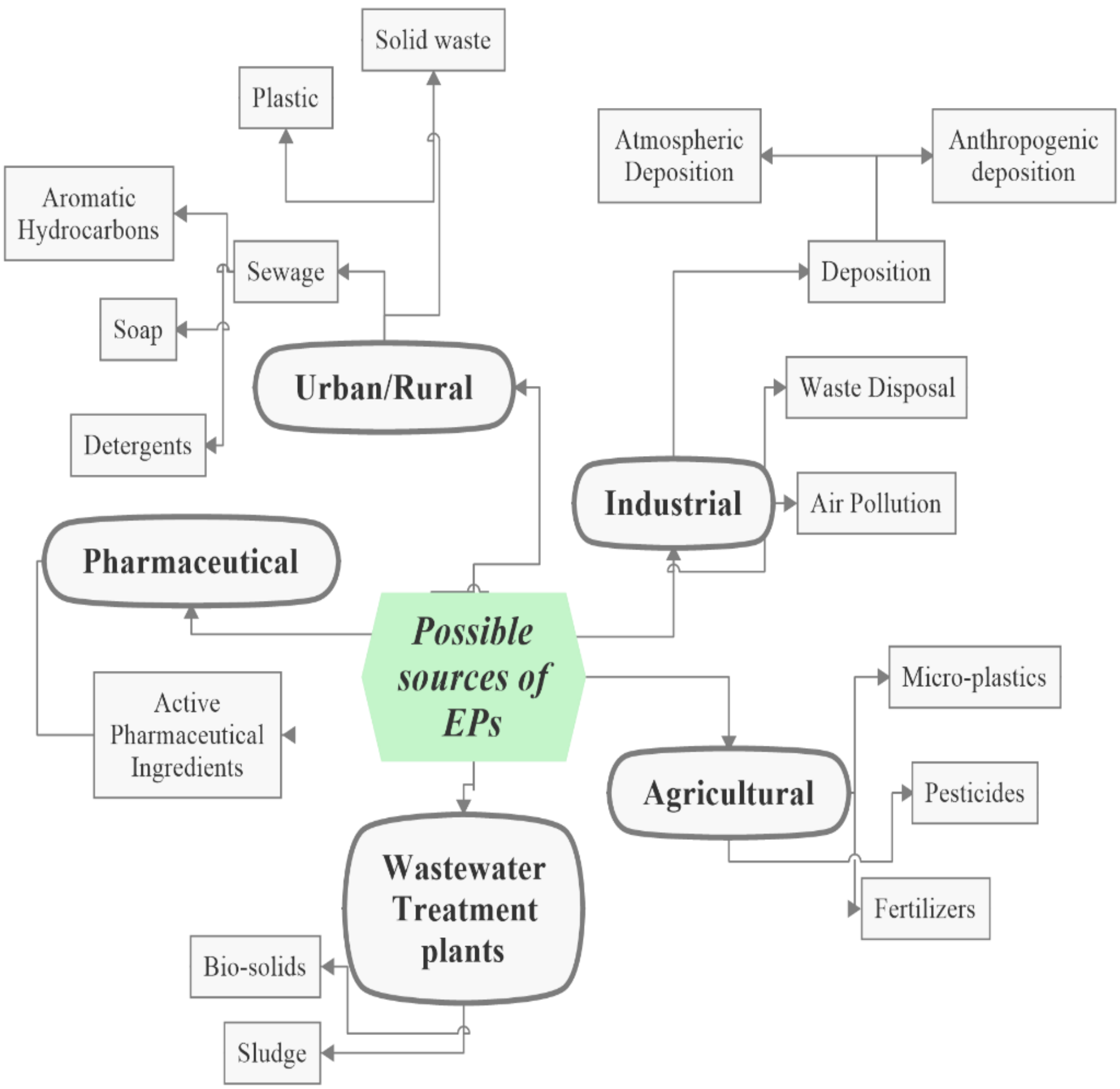

Figure 1. The potential sources of environmental pollutants (EPs) encompass diverse settings, ranging from urban and rural locales to industrial, agricultural, pharmaceutical, and wastewater treatment facilities. These sources stem from anthropogenic activities associated with the production, utilization, and disposal of various commodities.

Despite numerous strategies proposed to address contamination, phytoremediation has emerged as a preferred method. Phytoremediation involves using plants alone or in conjunction with soil microbes to mitigate the effects of pollutants in the environment. This approach is cost-effective and has gained wide acceptance as an environmental restoration technology, surpassing engineering methods that often harm soils. Phytoremediation can address various contaminants, with the specific technique employed dictating the types treated. Plants play integral roles throughout the process, from uptake and translocation to sequestration and eventual degradation of pollutants. After treatment, plants can be processed through methods such as ashing, composting, or drying [22, 23]. As a result, among the myriad soil pollution remediation approaches, phytoremediation stands out as a long-lasting, eco-friendly, and cost-effective solution [24]. Recent scientific advancements enable green plants to remove pollutants from the environment through their physiological processes. Consequently, extensive research has been conducted in this area, exploring the processes of phytoremediation and the utilization of natural or genetically modified plants to remediate harmful contaminants.

2. Mechanism of Phytoremediation

Phytoremediation, a sustainable approach utilizing green plants to extract, isolate, or detoxify contaminants from soil and water, is both cost-effective and environmentally friendly. Plants employ various mechanisms to mitigate contamination, such as absorbing and sequestering heavy metals in their tissues or breaking down organic pollutants, thus reducing their toxicity in the environment. Different plants utilize distinct strategies depending on the type and form of pollutants present in the soil or water. The overall process of phytoremediation is outlined in Figure 2, depicting techniques involved in removing hazardous pollutants. Its elaboration is based on phytoremediation techniques which are involved in the removal of hazardous pollutants from soil and water [25]. Phytoremediation can be used alone or in conjunction with other methods as the last stage in the remediation process. Phytoremediation can be employed independently or in conjunction with other remediation methods as a final step. It is intricately linked with the rhizosphere microbial community, which can influence the movement of inorganic substances, decomposition of organic pollutants, and plant growth through the production of phytohormones. This section highlights the natural processes of phytoremediation as a cost-effective solution for contaminated soils.

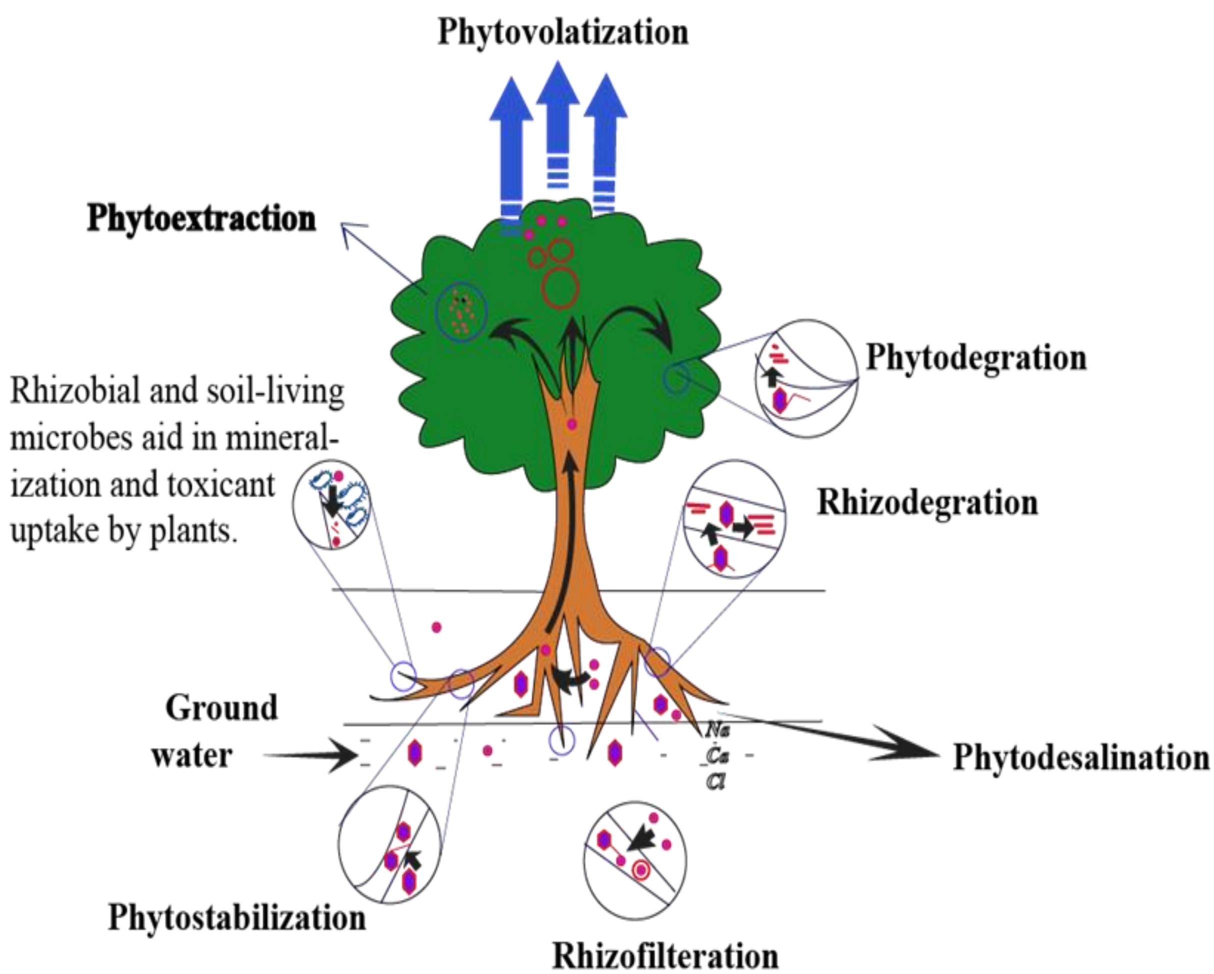

Figure 2. Depiction of different processes of phytoremediation. A concept from [25].

2.1. Phytoextraction

Phytoextraction, or phytoaccumulation, refers to the process wherein plant roots absorb hazardous metals from the soil. Certain plants, known as hyperaccumulators, excel in accumulating large quantities of these metals in their tissues and roots. Hyperaccumulator plants exhibit a high capacity for specific target elements, although only a limited number of plants are recognized as hyperaccumulators [26].

2.2. Plant Immobilization/Stabilization

Plant roots play a crucial role in stabilizing pollutants, reducing their mobility and bioavailability, thereby minimizing their negative effects. Through processes such as conjugation with sugar, protein, and amino acid derivatives, or the formation of complexes in the rhizosphere, heavy metals and some organic pollutants can be transformed into non-toxic molecules [27].

2.3. Rhizofiltration

Rhizofiltration involves using plant roots to remove harmful chemicals from wastewater, groundwater, or surface water. Contaminants are either adsorbed or absorbed by the plant roots, purifying the ground or surface waters. This method is particularly effective for cleaning up soil and water heavily contaminated with fertilizers like nitrogen and phosphorus [28].

2.4. Phytovolatilization

Phytovolatilization encompasses multiple stages. Initially, plants absorb pollutants from the soil, converting compounds from low to high-volatility forms before releasing them into the atmosphere. This method proves effective when the volatilized pollutants become less hazardous. Many plants possess the ability to volatilize dangerous organic contaminants, releasing them in a harmless form into the atmosphere through the volatilization mechanism [29].

2.5. Phytodegration

Phytodegradation refers to the alteration of pollutants upon exposure to light. While this term is often avoided, within the realm of phytoremediation, it serves as a valuable tool for remediation of various contaminants such as pesticides, polychlorinated biphenyls (PCBs), synthetic dyes, and others. For example, Bryophyta has been observed to absorb metals [30] and Phragmites australis demonstrated phytodegradation of ibuprofen (IBP) in a study [31]. The process of phytodegradation can be further enhanced by overexpressing desired genes in the plant, leading to increased uptake and metabolism of specific pollutants [23].

2.6. Rhizodegration

Rhizodegradation occurs when pollutants are degraded in the rhizosphere. Contaminated aquatic habitats can be treated through rhizofiltration, where pollutants are adsorbed or precipitated onto the roots or other submerged organs of metal-tolerant aquatic plants for removal. However, a significant disadvantage of this method is the need to cultivate the plants in a greenhouse before transporting them to the cleanup site [32].

2.7. Phyto-desalination

Phyto-desalination involves salt-tolerant plants absorbing large quantities of salt from the soil, thereby improving soil salinity and enhancing crop yields. This process reduces the saline soil's reduction potential, leading to dehydration and alterations in plant physiology [33]. Examples of plants contributing to phyto-desalination, such as Lonicera japonica and other halophytic species, are listed in Table 1, along with examples of plants utilizing similar processes for the phytoremediation of various contaminants.

Table 1. Few examples of plants that are reported to use different processes for phytoremediation of various contaminants.

Process	Name of plant	Scientific designation	Contaminants	Ref.
Phytoextraction	Lettuce	*Lactuca sativa.*	Ni, Fe, & Co.	[34]
	Perennial rye grass	*Lolium perenne.*	Ni, Fe, & Co.	
	Geranium	*Pelargonium hortorum.*	Pb.	[35]
Phyto-stabilization	Willow	*Salix sp.*	Cd.	[36]
	Sunflower	*Helianthus annuus.*	Ni, As, Pb, Cu, Cd, Hg & Zn.	[37]
	Black nightshade	*Solanum nigrum.*	Zn, Cd, Cu.	[38]
Rhizofiltration	Water hyacinth	*Eichhornia crassipes.*	Cu, Cd, Zn, Ni, As, Fe, & Cr.	[39]
	Duckweed	*Lemna minor.*	U	[40]
	Water starwort	*Callitriche lusitanica.*	As.	[41]

Phytovolatilization	Rabbit foot grass	*Polypogonmon speliensis.*	As.	[42]
	Perennial reed grass	*Phragmites australis.*	OCs	[43]
	Common rush	*Juncus effuses.*	Ammonium	[44]
Phytodegradation	Coral	*Ipomoea carnea.*	Azo dyes from Textiles	[45]
	Perennial reed grass	*Phragmites australis.*	Ibuprofen.	[31]
	Duck weed	*Spirodela polyrhiza.*	OFX	[46]
Rhizodegradation	Chinaberry tree	*Melia azedarach.*	Benzo(a)-pyrene	[47]
	Bermuda grass	*Cynodon dactylon.*	TPHs	[48]
	Maiz	*Zea mays.*	Petroleum	[49]
Phyto-desalination	Alkali grass	*Puccinellia nuttaliana.*	Chloride ion Sodium ion	[50]
	Alligator weed	*Alternanthera philoxeroides.*	Sodium ion	[51]
	Water spinach	*Ipomoea aquatica.*	Sodium ion	

OCs – Organochlorines, OFX-Ofloxacin, TPH-Total Petroleum Hydrocarbons

3. Augmentation of Phytoremediation

The primary function of phytoremediation is to render the pollutants harmless by using hyperaccumulators [52]. For instance, there are two approaches for the phytoremediation of organics: (a) direct phytoremediation -the uptake/absorption of contaminants through the roots and transfer to the top section of the plant is referred to as direct phytoremediation; (b) Phytoremediation explanta - pollutants are solely limited to the rhizosphere in explanta phytoremediation. Because, the contaminants are exclusively retained or destroyed in the rhizosphere, explanta remediation is also known as rhizoremediation. Plants produce numerous enzymes and promote microbial proliferation in the rhizosphere for pollution accumulation or co-precipitation in this sort of clean-up [53]. In this way, plants can take up high levels of contaminants well within their structure through their roots. The hyperaccumulators are manipulated to accumulate 50-100 times more metals than normal plants. There are varying degrees of accumulation within plants that can often result in 1-5% of their total dry weight [54, 55]. An example can be found in the species of Thlaspi, which can accumulate Zn, Pb, Cd, and Ni [56-59].

3.1. Enhancing Phytoremediation Potential through Genetic Modifications

The efficacy of plants as hyperaccumulators hinges on their phytoremediation potential, which is often hindered by limitations such as slow growth and suppressed growth under adverse environmental conditions [60, 61]. To overcome these challenges and bolster their effectiveness in remediation efforts, plants are modified and improved. Essential traits for effective phytoremediation include a well-developed root system, rapid shoot growth, abundant shoot biomass, and the ability to store and tolerate high metal concentrations. One approach to achieving these traits involves introducing hyperaccumulation traits to enhance growth rates and biomass production [62]. Techniques such as plant-microbial associations and recombinant DNA technology (rDNA technology) are employed to enhance plant abilities by characterizing and engineering the genetic makeup of plants to optimize their phytoremediation capabilities.

3.2. Harnessing Microorganisms for Enhanced Phytoremediation

Microorganisms associated with plants, as well as soil-dwelling animals, play a crucial role in augmenting the phytoremediation capabilities of plants by facilitating their growth and development. Approximately 20,000 plant species are known to rely on microbial symbiosis for their survival and growth [63]. Mycorrhizal fungi, both parasitic and symbiotic, along with free-living or endophytic bacteria, contribute significantly to plant growth enhancement and have been effectively utilized in phytoremediation processes [64]. For example, rhizobia bacteria form symbiotic relationships with leguminous plants, facilitating atmospheric nitrogen fixation into ammonia compounds, thus playing a vital role in nitrogen recycling within agricultural ecosystems [65].

3.3. Advancements in Phytoremediation through Biotechnology

Biotechnology has revolutionized phytoremediation, addressing its key limitations by facilitating the development of rapidly growing plants with enhanced pollutant accumulation capacities [66]. This progress is further propelled by the deepening understanding of enzymatic activities and xenobiotic metabolism, enabling the identification and engineering of specific enzymes crucial for pollutant degradation. For instance, transgenic tobacco plants containing the human P4502E1 gene exhibited a remarkable 640-fold increase in trichloroethylene transformation compared to non-transgenic counterparts, showcasing improved metabolism and uptake of various halogenated hydrocarbon contaminants in groundwater. Such GM plants demonstrated improved metabolism and uptake of ethylene dibromide and several halogen derivatives of hydrocarbons contaminating the groundwater. Initially, transgenic crops - plants with the required gene for improvement of phytoremediation- were developed to lessen the amount of pesticide required to decrease yield loss [23, 67]. Initially focused on reducing pesticide usage in agriculture, transgenic crops have now expanded their scope to remediate a wide range of pollutants, including heavy metals, phenolics, explosives, and organic compounds, owing to advancements in recombinant DNA technology [68]. By incorporating genes from microorganisms, animals, and other plants, plants can be engineered to express metal transporters and other remediation-related proteins, while transgenic approaches involve both overexpression of endogenous genes and the incorporation of genes from model species into hyperaccumulators like members of the Brassica genus [69]. These developments underscore the promising potential of transgenic crops and gene editing techniques in reclaiming polluted soils and water bodies.

4. Soil Contamination and Phytoremediation

4.1. Impacts of Soil Pollution on Agricultural Ecosystems

Agricultural soils face contamination from various sources, including fertilizers and pesticides, which can lead to long-term detrimental effects [70]. Heavy metals, such as cadmium (Cd), accumulate in crops when watered with contaminated water or overexposed to mineral fertilizers or manures, posing risks to crop health [71, 72].

Industrial waste is a significant contributor to soil pollution, with irresponsible disposal practices by industrial companies exacerbating the problem [73-76]. Soil erosion caused by deforestation further exacerbates soil pollution by allowing soil particles to be carried away by water or wind [77]. This pollution not only disrupts the natural ecosystem balance but also affects soil microbiota, leading to the demise of vital organisms like earthworms and rhizobacteria [78]. Normally, crops cannot grow and thrive if the soil is contaminated. If some crops do manage to thrive, the hazardous chemicals in the soil may have been absorbed by the crops, causing major health problems for those who consume them [79]. Much of the microbiota (e.g. earthworms, rhizobacteria) may perish as a result of soil pollution altering the soil structure. Consequently, contaminated soils not only hinder crop growth but also pose serious health risks to consumers due to potential chemical absorption by crops [71].

4.2. Phytoremediation of Organic Contaminants

Plant roots possess intricate physiology and biochemistry, rendering them effective remediators of harmful organic contaminants [71, 80]. Common organic pollutants and toxic volatile organic compounds (VOCs) found in agricultural soils, such as trichloroethylene (TCE), vinyl chloride, polychlorinated biphenyls (PCBs), chloroform, benzene, and carbon tetrachloride, pose significant environmental concerns [81-83]. To address this, transgenic plants engineered to overexpress human cytochrome P450 enzymes, which play a crucial role in metabolizing these chemicals, are being developed [84]. However, the detoxification process in plants can be slow, leading to the accumulation of harmful substances that may eventually be released into the environment. As an alternative approach, extracellular enzymes like laccases and peroxidases are being explored for the phytoremediation of small organic pollutants [85, 86].

4.3. Plant-Mediated Degradation of Trichloroethylene (TCE)

Plants possess aliphatic dehalogenases capable of degrading trichloroethylene (TCE), a widespread environmental contaminant in agricultural soils and a prominent industrial solvent known to pose risks to both animals and humans. TCE and other halogenated chemicals are notoriously difficult to break down and often exhibit toxicity and carcinogenic properties. However, plants grown in contaminated areas have demonstrated the ability to accumulate TCE, transpire it efficiently, and enhance its breakdown by supplying biodegrading bacteria with root exudates in the rhizosphere. Plant enzymes, on the other hand, have just lately been discovered to have a direct part in the degradative process. Axenically grown poplars aggressively take up TCE and break down it into trichloroethanol, chlorinated acetates, and eventually CO2, according to mass-balance and isotopic labeling investigations. These findings suggest the existence of an oxidative degradation pathway in plants, contrasting with the reductive pathway observed in bacteria [87, 88].

4.4. Phytoremediation of Nitroaromatic Chemicals

Nitroaromatic chemicals, notorious for their extreme toxicity and carcinogenicity, including the explosive TNT (2,4,6-trinitrotoluene), pose significant contamination challenges in land and water bodies near manufacturing, storage, and disposal sites. Despite their resistance to degradation, certain plant species have demonstrated the ability to degrade nitroaromatic compounds, with CO2, ammonium, or nitrate identified as end products. While, many plant species show some degree of TNT degradation capability, only a few are highly effective in this regard. For instance, Microphyllum aquaticum and Catharanthus roseus hairy root cultures have been found to efficiently degrade TNT, with degradation intermediates released into the growth medium. Similarly, sugar beet cell cultures have been shown to break down glycerol trinitrate (GTN) into glycerol dinitrate and glycerol mononitrate. Hairy root cultures of Catharanthus roseus were capable of decomposing significant amounts of TNT within a short period, highlighting the potential of plant-based remediation strategies for nitroaromatic contamination [89, 90].

4.5. Phytoremediation of Polychlorinated Biphenyls (PCBs)

Polychlorinated biphenyls (PCBs) present severe environmental challenges due to their carcinogenicity, toxicity, and slow biodegradation rates. However, various plant species have demonstrated effectiveness in degrading different types of PCB congeners. For instance, axenic cultures of Solanum nigrum have shown rapid degradation of numerous PCB congeners in sterile environments. PCBs with higher degrees of chlorination present greater challenges for both bacteria and plants in terms of degradation. Additionally, a recent study highlights the potential of transgenic alfalfa plants containing bacterial genes, such as bphc, which encode bioemulsifier protein AlnA, to enhance PCB desorption in soil, thus offering promising prospects for PCB remediation efforts [90, 91].

5. Heavy Metals and Phytoremediation

5.1. Impact of Heavy Metals on Living Organisms

Heavy metals are categorized into essential, including Ni, Cu, Zn, Fe, Mo, and Mn, and non-essential, such as Cd, Pb, and Hg [92]. While essential heavy metals are vital for various metabolic functions in humans and plants, they can become toxic at elevated concentrations, leading to cellular damage [93]. For instance, copper (Cu) is essential for hemoglobin formation and carbohydrate metabolism but can be harmful when accumulated excessively Hg [92, 94]. In plants, heavy metals serve as cofactors, enzyme activators, and stabilize cation reactions, but their high levels can impede growth and seed germination, disrupt biochemical reactions, and induce genetic variations [92, 95]. Even at low concentrations, non-essential heavy metals exhibit toxic effects, affecting soil pH, composition, and plant toxicity [96, 97]. Food contamination by heavy metals poses clinical risks upon consumption, as these metals cannot be metabolized or degraded in the environment, persisting in ecosystems and disrupting food chains upon release from households, industries, and agricultural sources [98, 99].

5.2. Enhanced Heavy Metal Tolerance in Transgenic Plants

Plants absorb heavy metals as essential micronutrients, but high concentrations can pose challenges to natural plant growth [7-9]. Transgenic plants, however, exhibit increased tolerance to heavy metal contamination, with the development of transgenic plants initially focused on enhancing heavy metal tolerance for phytoremediation purposes [100, 101]. Numerous genes have been identified to enhance heavy metal tolerance upon insertion into plants [102]. For example, the insertion of the STGCS-GS gene from Streptococcus thermophilus into Beta vulgaris has been reported to enhance tolerance to cadmium, zinc, and copper in the host plant

[103]. Similarly, poplar plants engineered with the ECS gene from Escherichia coli showed improved flux and detoxification of cadmium, facilitated by the associated enzyme "γ-glutamylcysteine" synthetase [104].

5.3. Phytoremediation of Heavy Metals through Transgenic Plants

Phytoremediation of heavy metals can be effectively achieved through transgenic plants, engineered to exhibit high tolerance and uptake of heavy metals, particularly for in-situ remediation approaches [105]. Studies have demonstrated the efficacy of genetically engineered plants in this regard, as highlighted in Table 2. A recent example includes the development of transgenic Sedium alfredi, where the introduction of the SaNramp1 gene from Pseudomonas fluorescens enhanced zinc uptake through an associated Fe-regulated transporter [106]. Additionally, plants can facilitate heavy metal remediation by providing a conducive habitat for microorganisms involved in bioremediation processes. For instance, the symbiotic association of bacteria with remediation capabilities with leguminous plants exemplifies one such approach [65].

Table 2. Some studies that demonstrated effectiveness of genetically engineered plans in phytoremediation

Contaminant	Plant	Gene	Source	Ref
Cd, Zn, and Cu	*Beta vulgaris*	STGCS-GS	*Streptococcus thermophilus*	[103]
Cd	*Poplar plant*	ECS	*E. coil*	[104]
As	*Wild-type rice*	OsARM1	*Oryza sativa*	[107]
Cd, Pb, Zn	*Urtica dioica*	CUP	*Bacillus shackletonii*	[108]
As	*Nicotiana tabacum*	AtACR2	*Arabidopsis thaliana*	[109]
Cd, Zn	*Arabidopsis thaliana*	PCs	*Morus alba*	[110]
Cd, Zn	*Brassica napus*	OsMyb4	*Oryza sativa*	[111]
Cd	*Arabidopsis thaliana*	PCs1	*Brassica napus*	[112]
Cd	*Arabidopsis thaliana*	PCs1	*Vicia sativa*	[113]
Cd, Zn	*Brassica napus*	CKX2	*Arabidopsis thaliana*	[114]
Cd, Cu, Mn, Zn	*Nicotiana tabacum*	LmSAP	*Lobularia maritima*	[115]
Polychlorinated Biphenyls (PCBs)	Alfalfa	bphc	*Soil metagenomic library*	[91]

Cu, Cd	*Oryza sativa*	ricMT	*Oryza sativa*	[116]
Zn	*Sedium alfredi*	SaNramp1	*Pseudomonas fuorescens*	[106]

6. Air Contamination and Phytoremediation

6.1. Impact of Air Pollution on Human Health and Ecosystem

Air pollution, driven by increased concentrations of greenhouse gases and aerosols, poses significant risks to human health and ecosystems [14, 117, 118]. Human activities like industrial operations and combustion processes contribute substantially to this phenomenon, with natural events like volcanic eruptions and wildfires playing a smaller role [119, 120]. Air pollution leads to respiratory illnesses, skin disorders induced by oxidative stress, and exacerbation of existing skin conditions [121-123]. Prolonged exposure to high levels of pollutants can also result in extrinsic skin aging and skin cancer [124].

6.1.1. Composition and Impact of Aerosols in the Atmosphere

Nitrogen and oxygen constitute the majority of Earth's atmosphere, comprising approximately 99.9%, with nitrogen at 78% and oxygen at 21%, while argon accounts for 0.9%. The remaining 0.1% consists of trace gases such as water vapor, carbon dioxide, ozone, methane, neon, and various compounds of helium and nitrogen [125]. Additionally, undissolved solids and moist particles, collectively known as aerosols, are present in the atmosphere, ranging in size from micrometers to millimeters. Aerosols originate from sources like sea salt, soil, dust, and volcanic eruptions. They play a crucial role in the formation of polar stratospheric clouds (PSCs), which contain water and nitric acid hydrates and are closely linked to the ozone hole over Antarctica. Furthermore, aerosols influence radiation balance by scattering visible light and absorbing infrared radiation emitted by the Earth's surface [126].

The accumulation of synthetic trace gases within the ecosystem poses significant threats, potentially leading to future planetary warming or ozone depletion. Human activities, particularly the increase in naturally occurring gases like nitrogen dioxide and methane, are expected to exacerbate the greenhouse effect on Earth. Synthetic halogenated hydrocarbons, such as CCl2F2 (F-12) and CCl3F (F-11), are also anticipated to contribute significantly to global warming [127]. Moreover, trace gases can react with atmospheric substances to form aerosols, fine particles that have the ability to absorb light and impact both the environment and human health. Infiltration of these particles into the respiratory system can result in serious health implications [128].

6.2. Genetically Modified Plants for Enhanced Bioremediation

Genetically modified plantations offer a promising and cost-effective solution for the rapid elimination of chemicals, toxins, and explosive remnants [129]. Vegetation-enhanced bioremediation harnesses the symbiotic relationship between plants and microbes in the rhizosphere and phyllosphere to mitigate atmospheric pollutants. In a study, Petunia plants were transformed using the K599 strain of Agrobacterium rhizogenes, with confirmation of the rolB gene from the Ri plasmid and the CYP2E1 transgene achieved through PCR analysis [130, 131]. Southern blotting, a laboratory technique, further confirmed the presence of multiple copies of the CYP2E1 gene in genetically modified plants. The CYP2E1 protein, a member of the P450 enzyme group, plays a crucial role in metabolizing small molecules and organic contaminants, including volatile organic compounds (VOCs) [132, 133].

6.3. Reducing Methane Emissions with Genetically Modified Plants

Methane, a potent greenhouse gas (GHG), contributes to ozone formation and adversely affects air quality, crop yields, and human health [134, 135]. Neil Farbstein, Head of Clean Energy Research Foundation Inc., proposed a method to mitigate global methane emissions using existing methane monooxygenase (MMO) enzymes. By genetically modifying plants to produce MMO and sowing them on vast lands, Farbstein's idea aims to combat global warming caused by methane accumulation. However, environmentalists caution that while some methane is necessary to prevent ice ages, managing the rapid proliferation of modified plants with additional MMO enzymes is crucial to ensure they remain on land soil [136].

6.3.1. Controlling Methane Emissions from Cattle with Modified Forage Plantations

To address methane emissions from cattle and similar animals, surrounding fields with modified forage plantations and trees can help break down and eliminate methane from the air. Additionally, modifying grasses near swamps and wetlands for methane oxidation presents another avenue for reducing methane levels [137].

6.4. Enhancing Phytoremediation with Transgenic Poplar Trees

Fast-growing tree species from the genus Populus, such as poplar trees, are considered ideal candidates for phytoremediation due to their ability to reduce concentrations of organic environmental pollutants like chloroform, benzene, and trichloroethylene (TCE) [138, 139]. However, traditional phytoremediation methods are often slow and ineffective for treating hazardous materials like trinitrotoluene (TNT) and Royal demolition explosive (RDX) [67, 129, 140]. To address this, specific genes are introduced into transgenic plantations. For example, the expression of glutathione S-transferase or Cytochrome P450 (CYP450) genes in transgenic plants has improved the phytoremediation of herbicides and other contaminants such as C6H6, vinyl chloride, etc., [141]. The incorporation of the mammalian enzyme Cytochrome P450 2E1 (CYP2E1) into Nicotiana tabacum resulted in enhanced metabolic performance of TCE, leading to transgenic trees capable of removing or degrading harmful impurities from both aqueous and gaseous environments [133]. In experimental trials, CYP2E1 transgenic cottonwood plants showed significant efficacy in eliminating TCE and benzene from the air, demonstrating improved phytoremediation capabilities compared to control plants [142].

6.5. Phytoremediation and Air Quality Improvement with Plants

In controlled experiments, potted plants in sealed chambers demonstrated remarkable effectiveness in removing gaseous VOCs reducing their levels by up to 90% within 24 hours [143]. NASA research underscores the importance of houseplants in pollution management, highlighting their ability to absorb and cleanse organic toxins. While biotechnological approaches in horticulture for eliminating particulate matter (PM) are relatively understudied, several plants have been identified for improving indoor air quality [85, 144-146]. Plants such as Spider plants and Devil's Ivy are known for their capacity to remove PM, with Spider plants or philodendrons, and Chlorophytum comosum being particularly effective at removing formaldehyde and PM, respectively [147].

Research suggests that larger plants tend to exhibit more effective botanical air filtration, owing to their increased surface area and air dynamics [143]. For instance, road dust, a complex environmental medium comprising vehicle emissions, air deposits, and industrial operations, poses significant hazards to both the environment and public health. This dust contains various microelements, with zinc (Zn) being a prominent component of particulate matter. Recent studies have highlighted the ability of plants to uptake heavy metals, leading to a reduction in atmospheric particulate matter levels. Smaller particles can penetrate leaf surfaces, while larger ones remain on the external wax surface. Additionally, plant species exhibit differences in their leaf epidermis and varying adsorption rates for particulate matter, indicating unique phytoremediation potential for environmental zinc contamination [148]. In a comparative study in 2017, fourteen tree varieties were assessed for their ability to deposit Zn in the environment, with Moms alba, Pinus eldarica, and Nigral morus species showing elevated bioaccumulation extents for heavy metals. These findings suggest their suitability for use in urban green shield areas to mitigate heavy metal levels [143, 149].

7. Conclusion

In conclusion, phytoremediation emerges as a promising eco-friendly, cost-effective, and sustainable solution for the remediation of environmental pollutants. Leveraging the natural capabilities of plants, coupled with advancements in microbial-assisted bioremediation and genetic engineering, offers unprecedented potential for effectively detoxifying contaminated soils, wetlands, and water bodies. The utilization of transgenic plants enhances the extraction and detoxification of pollutants, further bolstering the efficacy of phytoremediation. However, the ongoing efforts to modify plants with desired genes must be accompanied by comprehensive risk assessment studies, including long-term field observations, to ensure environmental safety.

Additionally, the potential risks associated with the dispersion of transgenic plants into wild-type populations necessitate the implementation of technologies such as genetic use restriction mechanisms to mitigate these concerns. Moving forward, continued research into the capabilities of various plant species for phytoremediation, along with the development of innovative technologies, will be essential for addressing environmental pollution and promoting sustainable ecosystems.

Author Contributions

Conceptualization, H.R., validation, G.Z.J.; formal analysis, J.R.; investigation, S.Q., S.F., M.M.; writing—original draft preparation, H.R.; writing—review and editing, G.Z.J.; supervision, G.Z.J. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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