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Review Article

A Review of mechanisms for controlling organic and inorganic pollutants through phytoremediation

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Abstract

This study indicates that the tremendous scientific and technological advancements—which have led to the economic development of the world and progress in various fields—have also given rise to new challenges, particularly in nature conservation and environmental protection. This is primarily due to the discharge of pollutants into the components of the ecosystem (water, air, soil), which serve as the ultimate repositories for these elements. Chemicals of natural or industrial origin that are discharged into the environment as a result of human activity are known as environmental pollutants, and they are detrimental to both the environment and human health. With an emphasis on the removal of both organic and inorganic pollutants, including heavy metals like lead, mercury, zinc, and cadmium, as well as on plants' capacity to accumulate high concentrations of toxic substances within their tissues without compromising their life cycles, the study examines phytoremediation techniques and their mechanisms of action. Compared to other mechanical methods, this technology is more stable and effective, is less expensive, and is ecologically benign. It is also used to remove a variety of environmental pollutants.Furthermore, the study highlights biotechnological techniques used to restore polluted water and soil environments to their natural state and emphasizes the development of phytoremediation technology for polluted lands. This is achieved by improving genetic traits and enhancing soil conditions—both physical and nutritional—to create an ideal environment for the growth of remediation plants. These plants break down or decompose organic pollutants and heavy metals, absorb them, stabilize them, and convert them into substances that are not harmful to the environment. In addition, the use of large trees, whose roots extend deep and far into the soil, is recommended because they are more effective than smaller plants in eliminating pollutants.

1. Introduction

The contribution of plants to combating environmental pollution is not a new concept. Since ancient times, plants have maintained environmental balance, and today they play a role in mitigating the Earth's rising temperatures by absorbing carbon dioxide (one of the greenhouse gases) and releasing the oxygen essential for life. With the tremendous advances in genetic engineering in recent years [1], scientists have discovered astonishing capabilities in plants and green trees—namely, their great potential in countering recalcitrant pollutants, radioactive pollutants, and heavy metals.

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Technological progress and increasing population growth have led to a higher demand for consumer products and energy, resulting in the construction of more chemical factories, nuclear power plants, and oil refineries. These facilities have begun discharging their wastes—laden with various heavy metals as well as hazardous, toxic, and radioactive substances—into the environment's components: air, water, and soil. Exacerbating the danger of these pollutants is that most of them are persistent contaminants capable of bioaccumulation and biomagnification in living organisms [2].

This has resulted in the contamination of groundwater and surface water, the increase of polluted sites, and the buildup of harmful pollutants—such as heavy metals, radioactive nuclides, and organic contaminants—in soil and water across extensive areas globally.

Both the Netherlands and Canada have been found to have contaminated areas, according to environmental surveys. It was said in one of the reports that the Environmental Protection Agency of the United States of America that the total number of polluted sites in the United States requiring remediation over the next thirty years is estimated to cost approximately 250 billion dollars. Similarly, reports from the European Environmental Protection Agency show that the overall cleanup costs for polluted sites in the European Union range between 59 and 109 billion euros [3].

In light of this situation, the world has increasingly turned to phytoremediation techniques to clean polluted sites, groundwater, and soils contaminated by radiation. These techniques are considered environmentally friendly and outperform other engineering remediation methods in both economic and technical terms. The term "environmental pollutants" was first introduced by Huntzinger and Veerkamp in 1981. They defined it as "chemical substances of industrial or natural origins that are released into nature as a result of human activities and have a harmful effect on the environment and humans."

There are tens of thousands of chemicals used in industry, agriculture, households, hospitals, tanneries, livestock farms, and smelters. In developing countries, the number of organic chemicals used in industry is estimated to be around 50,000 compounds, in addition to thousands of pesticides employed to eradicate weeds and insects [4]. What further complicates the remediation of chemical pollutants is that they differ extensively in the nature of the substances, their reactions, decomposition products, and their effects on organisms [5]. Despite these compounds possessing organic characteristics, they cannot, for example, be decomposed by enzymes because most of them are originally organic compounds in which hydrogen atoms have been replaced by chemical groups. Consequently, they have lost the properties of their original organic substances—whether those origins were sugars, amino acids, or other compounds—and therefore, the well-known principles of organic chemistry regarding reactivity, decomposition, and related processes do not apply to them [6].

What are Phytoremediation and Bioremediation?

Phytoremediation is derived from two terms: "Phyto," signifying "plant," and "Remediation," denoting "restoration" or "treatment." This strategy involves specific plants and soil organisms transforming toxins detrimental to humans and the environment into innocuous—and often advantageous—forms. This approach is increasingly employed to remediate sites contaminated with heavy metals, hazardous organic chemicals, and radioactive elements [7].

This method involves the removal of certain pollutants—whether organic or inorganic—from contaminated sites such as agricultural soils and water. It is one of the important, simple, and inexpensive approaches that do not cause environmental damage. In practice, plants are cultivated in polluted areas where they absorb large amounts of substances into their biomass, including roots, stems, and leaves [8]. Subsequently, the plants are processed, and some of the recoverable materials are recycled for use in various industries. This method is especially useful for recovering important industrial metals such as copper and tin.

The sensitivity of plants varies in their ability to grow and absorb heavy metals or organic compounds. Therefore, the most effective plants are selected after extensive studies. Research indicates that many plants can be used in this field—such as fast-growing wild herbaceous plants with high biomass [9] —or plants that can biologically absorb and accumulate toxic trace elements, including heavy metals like lead and cadmium, as well as selenium, and even certain types of grasses and seasonal crop plants such as sunflowers [10].

Nevertheless, bioremediation is the process of identifying a living organism that can remove a portion of the pollutants that are present in our environment (water, air, soil). It is anticipated that the treated pollutant will be transformed rather than merely eliminated when a living organism—whether a plant, animal, microorganism, or bacterium—is selected to remove specific environmental pollutants. new compounds are produced that are easier to analyze environmentally, inert compounds that are not harmful to the environment, or compounds that are less hazardous than the original substance [11]. The resulting products must be thoroughly tested to ensure they do not become more hazardous.

The remediation of contaminated sites by traditional approaches has frequently proven to be costly, inefficient, and applicable only to restricted areas. Moreover, these procedures often render the soil unfit for agricultural use and do not address the issue effectively. In Germany, traditional cleanup facilities address just 30% of the contaminated soil at polluted sites, with the remainder being held in waste disposal facilities [12]. This highlights the significance of bioremediation:

- Changing active substances into inactive ones.
- Eliminating materials like plastic that take a long time to break down.
- Converting contaminants into harmless substances, or at the very least, inactive substances.
- Protecting the environment and human life.
- Handling contaminants like asphalt that cannot be chemically treated.

In reality, conventional methods do not address the problem at its roots; they merely postpone it for future generations. Therefore, there is an urgent need to develop alternative, environmentally friendly, inexpensive, and effective methods for cleaning industrially polluted areas that take into account the potential final use of the soil after remediation. This is precisely what phytoremediation offers: a low-cost and effective technique that can treat a wide range of pollutants and be applied to large areas of land, and most importantly, it does not destroy the remediated soil, which can be used for agriculture after cleaning [13].

Phytoremediation Mechanisms

Phytoremediation technology works by extracting, storing, transforming, and degrading various types of pollutants using the roots, stems, and leaves. It does so through several mechanisms [14].

Phytoextraction: This mechanism, also known as extraction or accumulation, involves the uptake of heavy metals from the soil into the plant's green biomass. Some plants are referred to as phytoaccumulators because they absorb larger amounts of metals compared to other species. After a period of growth, the plant is harvested and disposed of by incineration or by re-extracting the metals from its biomass. This method is useful for reducing soil contamination to acceptable levels [15], with the resulting ash disposed of at hazardous waste sites. The metals targeted for removal by this mechanism include nickel, copper, and zinc. Currently, studies and experiments are underway on various plant species for the uptake of lead and chromium in contaminated soils, and recent successful experiments have utilized the Chinese brake fern (Pteris vittata) for the uptake of arsenic from arsenic-contaminated soils, as this plant grows rapidly in such conditions [16].
Rhizofiltration: In this method, contaminants are adsorbed, absorbed, or precipitated by the roots in the plant rhizosphere. Rhizofiltration, akin to phytoextraction, is utilized for groundwater purification, whereas phytoextraction is employed for soil remediation. Plants are either cultivated directly in dirty water or contaminated water is transported to cultivation regions, enabling plants to absorb the tainted water. Upon the plant's saturation with contaminants, it is harvested. A significant application of this process is the utilization of sunflowers to remediate water bodies contaminated with radiation subsequent to the Chernobyl reactor explosion in Ukraine [17].
Phytostabilization: This technique utilizes specific plant species to attain the mechanical stability of polluted soil. The objective is to inhibit the dispersion of contaminants in soil or groundwater due to erosion or wind, hence minimizing their transmission to adjacent ecosystems—especially into the human food chain. Phytostabilization encompasses the absorption and buildup of contaminants in the roots, their adsorption onto root surfaces, or their precipitation within the rhizosphere. This method is frequently employed to rehabilitate vegetation cover in regions where soil quality has declined due to elevated levels of heavy metals [18].
Phytodegradation: This technique utilizes plants and their associated microorganisms to decompose organic contaminants, including ammunition residues, polychlorinated biphenyls (PCBs), and certain chlorinated solvents [19]. Phytodegradation entails the direct decomposition of organic contaminants through enzymes released by the roots or through metabolic activities inside the plant tissues. The efficacy of this mechanism relies on the availability of organic contaminants that can be assimilated and metabolized by both the plants and their symbiotic microbes. The extent of bioavailability is affected by the intricacy of the pollutant's chemical composition, its age, and the soil type. Hoor trees have been utilized in several applications utilizing this method to decompose hazardous and recalcitrant chemical substances [20].
Phytovolatilization: Through the process of absorption and volatilization, organic contaminants are taken up by plants from soil or water and subsequently released into the atmosphere. High transpiration and evaporation rate plants are typically employed, and the more volatile the pollutants, the simpler it is to remediate them with this technique. This approach can effectively remove volatile organic compounds (VOCs), for instance [1]. This technique, which uses genetic engineering advancements to transform mercury (in its ionic form) into less dangerous elemental mercury and release it into the atmosphere, has been used to remove mercury from contaminated areas. In certain uses, metals like mercury, arsenic, and selenium have been converted into organic compounds (called organometallic compounds) to make it easier for plants to handle them biologically.
That is, the removal of both organic and inorganic soil pollutants that exist as volatile compounds via plants. The main processes related to the volatilization of pollutants by plants include:

- The conversion of organic pollutants into volatile compounds from plants, aided by microorganisms.
- Reduction to volatile elements.
- The synthesis of volatile methyl and dimethyl compounds of certain metals and halides.
- The presence and activity of certain specialized enzymes to degrade these compounds, which is essential for completing the biochemical reactions [21].

Types of Pollutants According to Their Chemical Nature

High-risk soil pollutants can be divided into four groups [22]:

- Heavy metals
- Polycyclic aromatic hydrocarbons
- Chlorinated pesticides

Phytoremediation Applications

The effective implementation of phytoremediation necessitates the meticulous selection of plant species for the extraction of heavy metals, the degradation of organic compounds, and the remediation of polluted soil. In recent years, researchers have undertaken comprehensive experiments to acclimatize specific plant species to thrive in soils contaminated with heavy metals, including lead, nickel, zinc, and copper, as well as organic pollutants such as trinitrotoluene (TNT) and trichloroethylene (TCE).

Most phytoremediation research [23] has focused on cleaning sites contaminated with a single type of pollutant. For example, the Indian mustard *(Brassica juncea)* has been used for the phytoextraction of lead from contaminated soil, and poplar trees have been used to extract and degrade organic pollutants and some heavy metals.

In a study conducted by researchers at the University of Washington, it was found that the organic solvent trichloroethylene (TCE)—a cleaner used to remove oils and greases from metals that causes damage to the nervous system as well as destruction of the kidneys and liver—can be remediated using hybrid poplar trees *(Trichocarpa deltoides)* [24]. In other studies, this plant species was used to remove heavy metals and nitrates from soil and groundwater, respectively. In Sweden, poplar and willow trees have been used as biological filters to remove cadmium from sewage sludge (the residues resulting from the biological treatment of wastewater) in order to produce biomass that is later converted into energy.

The peace lily *(Spathiphyllum)* has also been used as an air purifier to remove formaldehyde and benzene (both carcinogenic pollutants found in gas and oil), as well as trichloroethylene from polluted air. In one study, certain plants such as *Sargassum, Ulva,* water hyacinth *(Eichhornia crassipes)*, and *Ceratophyllum demersum* were used. These plants were cultivated in either aquatic or terrestrial environments, where they work to transform pollutants—including dyes, pharmaceuticals, agricultural chemicals, heavy metals, petroleum and petrochemicals, and chemicals generated from industrial or laboratory waste that are discharged into water or soil—and purify the water or soil through their absorption [25].

As previously discussed regarding phytoremediation mechanisms, plants secrete natural substances through their roots to stimulate bacterial microorganisms to feed and perform their natural role in biologically eliminating pollutants (i.e., degradation). Alternatively, some plants sequester pollutants in their leaves and in certain cells, keeping them away from areas where they might cause harm. In other cases, plants secrete substances that stabilize or immobilize pollutants by converting them from a liquid state into a solid state, thereby preventing them from leaching into groundwater. In addition, the plant may extract water containing organic pollutants, purify the water, and remove the pollutants before discharging them either into the air or through its leaves .

The objective of phytoremediation is to generate new compounds that are easier to analyze environmentally, to produce inert compounds that are non-harmful to the environment, to reduce the use of chemicals in pollutant remediation, and to save the lives of aquatic animals and plants. It also aims to clean the soil of pollutants and reuse it, to preserve water resources and reuse the remediated water, as these plants function as environmental filters and provide a healthy and suitable habitat for living organisms [26].

The acid plant *ForsskvermiculateSuaeda and BiossmaurorumAlhagi* are among the most prominent species found in saline and wet areas in Iraq in general—and in the south in particular—due to their ability to withstand the environmental and climatic conditions characteristic of the region; consequently, they are used as bioindicators of pollution. Studies indicate that there are hundreds of resistant plant species used in phytoremediation, which are distributed among plant families such as Asteraceae, Brassicaceae, Cucurbitaceae, Fabaceae, Boraginaceae, and Buxaceae [27].

Researchers at Savannah University are working on developing a phytoremediation technology capable of addressing sites contaminated with various types of waste. It is expected that poplar trees will provide an ideal remediation solution for such sites due to their rapid growth, deep root systems, the abundance of microorganisms associated with their roots, and most importantly, their ability to adapt [28].

Uses of Poplar Trees

Another significant application in this field is the use of poplar trees, through the enzymes present in their roots, to alter the chemical composition of polychlorinated biphenyls (PCBs). PCBs are a group of persistent pollutants that vary in their properties and toxicity and have garnered increasing global concern due to their hazardous nature. These compounds are known to cause cancer and damage the nervous system in living organisms. Despite the fact that PCB production ceased more than 30 years ago, these compounds remain present in the environment due to their resistance to degradation and decomposition. Consequently, they have led to contamination of numerous soil and water sites across the United States, including the Hudson River. Reports from the U.S. Environmental Protection Agency indicate that more than 300 PCB-contaminated sites are listed as top priorities in the Superfund program for hazardous waste cleanup [29].

Currently, a joint research team from the Chinese Academy of Sciences and the University of Iowa is investigating the ability of poplar trees to modify the chemical structure of PCBs and convert them into less harmful compounds for humans and the environment.

Other studies have explored the use of alfalfa and juniper trees to remove petroleum and hydrocarbon contaminants from soil and groundwater. Additionally, successful experiments have been conducted using parrot feather plants and algae to eliminate explosive and ammunition waste [27].

Contributions to Mitigating the Effects of Chernobyl

Several years prior, the International Atomic Energy Agency performed an evaluation of the health and radiological conditions in the vicinity of the Chernobyl plant in Ukraine. The findings revealed that emissions of radioactive substances and heavy metals, such as iodine, cesium, strontium, and plutonium, remain concentrated in the soil, water, flora, and fauna, despite the passage of many years since the Chernobyl reactor disaster in 1986. Certain wild plants, including cranberries and mushrooms, have demonstrated elevated cesium concentrations, and the Canadian Nuclear Association noted a significant rise in thyroid diseases in regions adjacent to the nuclear incident [30].

Radioactive contaminants infiltrate the food chain via the grazing of sheep and cattle that consume vegetation cultivated in contaminated soil, resulting in the accumulation of poisons in meat and dairy products ingested by humans. A startup has recently engineered genetically modified sunflower strains that can eliminate 95% of radioactive pollutants in just 24 hours. Sunflowers were cultivated in a radiation-contaminated pond adjacent to Chernobyl; within 12 days, the concentration of cesium in their roots was 8,000 times larger than that in the pond water, and the concentration of strontium was 2,000 times higher than that in the pond water. The company cultivated industrial hemp to extract radioactive pollutants from the land adjacent to Chernobyl [31].

Aquatic Plants and Their Role in Environmental Remediation

Aquatic plants play a significant role due to their ability to grow in fresh water, which facilitates bioremediation and the purification of water from pollutants—especially in the rivers of major industrial cities that have posed a significant environmental problem. Among the modern applications of using aquatic plants is the investigation into the ability of the water hyacinth *(Eichhornia crassipes)* to remove phosphorus-based pesticides. This plant is expected to serve as an effective, economical, and environmentally friendly alternative for the removal and degradation of pesticide wastes, as well as for the disposal of agricultural industrial residues in general [32].

High efficiency in the environmental remediation of highly polluted aquatic systems has been demonstrated—particularly in systems where pesticides are used as chemical treatments. For comparison, the plant *Myriophyllum* was used, as its high sensitivity to various pesticide concentrations was observed compared to that of *Lemna*. In addition, [33] investigated the effectiveness of several aquatic plants, including *Ceratophyllum demersum*, *Wolffi*, and *Hydrilla verticillata*, in remediating certain highly polluted aquatic systems contaminated with heavy metals. He observed that cadmium significantly affected the levels of chlorophyll a and the protein content within plant tissues, with rooted plants such as *Hydrilla T4* exhibiting greater resistance to varying cadmium concentrations.

In contrast, Xue., [34] studied phytoremediation technology for restoring wetland environments and for the absorption and translocation of heavy metals in aquatic systems. He found an accumulation of copper in the cell walls of *Hydrilla verticillata* and observed that at a pH of 4.5 the chlorophyll and protein contents were adversely affected, accompanied by an increase in lipid peroxidation, whereas at a pH of 9.5 the toxicity of the element decreased markedly, with a corresponding increase in protein content. Moreover, [35] confirmed the presence of varying concentrations of heavy metals—cadmium, lead, and iron—in the tissues of *Ceratophyllum demersum* collected from oil-polluted areas.

Hamood [36] presented a study on the removal of certain industrial azo dyes—Brilliant Green (GR) and Congo Red (CR) —using some aquatic plants, assessing their responses through histological and physiological changes as well as through the analysis of genetic variations in the aquatic plants using a molecular marker.

The biological method employed to rehabilitate contaminated water and soil ecosystems entails utilizing living plants and their accompanying microorganisms to extract contaminants, including mining byproducts, fertilizers, and pesticides [37].

The elimination of heavy metals, petrochemicals, animal fertilizers, and compounds from sewage water treatment that contribute to soil contamination is addressed. Heavy metals are naturally present in soil in minimal quantities; they become pollutants when their concentrations above natural levels [38].

Pollutant-Tolerant Plants

The application of phytoremediation in contaminated soils depends chiefly on the plants' tolerance to contaminants, specifically their capacity to sequester elevated levels of harmful compounds in their tissues without impairing their life cycles. To cultivate pollutant-tolerant plants, it is essential to comprehend how plants mitigate the detrimental effects of both organic and inorganic contaminants [39].

2. Extraction of Inorganic and Organic Pollutants by Plants

Extraction of Inorganic Pollutants by Plants

Plants have the ability to remove pollutants from the soil, and recent studies have shown that the addition of certain chelating agents to the soil leads to an increased translocation of lead from the roots to the stems in some plants with high vegetative biomass, such as corn. It has been demonstrated that the chelating agent Ethylenediaminetetraacetic acid (EDTA) is highly effective in assisting plants in extracting large quantities of elements such as Zn, Pb, Ni, Cu, and Cd (from contaminated soils) [40].

The extraction of elements from contaminated soils by plants can be divided into two main categories:
- Absorption of elements by the roots
- Translocation of elements from the roots to the stems

Extraction of Organic Pollutants by Plants

Various types of plants have been selected to evaluate their ability to absorb organic pollutants from the soil. It has been found that the organic chemicals absorbed by plants are often moderately hydrophobic compounds—for example, atrazine, nitrobenzene, and trichloroethylene—whereas highly hydrophobic organic compounds tend to bind to lipophilic membranes and are unable to penetrate cellular membranes [40].

Phytodegradation of Organic Pollutants by Plants

The use of plants to degrade organic pollutants is an alternative to microbiological treatment for removing these pollutants from soil [41]. For example, the plants studied include hybrid willow *(Salix fragilis)*, bean *(Phaseolus)*, soybean *(Glycine max)*, wheat *(Triticum)*, corn *(Zea mays)*, alfalfa *(Medicago sativa)*, and spinach *(Spinacia oleracea)*. Degradation occurs as a result of:

Activation of the degradation of organic pollutants in the soil by microorganisms present in the rhizosphere. Degradation of organic pollutants in the soil by enzymes secreted by plants.Absorption of pollutants by plants, followed by chemical transformations that neutralize the toxicity of the original organic pollutants and convert them into mineral compounds within the plant cells [42].

Using Advanced Plants for Testing Soil Contamination

Numerous international methods have been evaluated to assess the toxicity of pollutants on advanced plants, as plant roots are among the most active biological surfaces. The degree of pollutant impact is evaluated by delayed root growth, inhibition of germination, and the emergence of seedlings above the soil surface in these two methods [43].

When testing soil contamination, it is advisable to use crops characterized by rapid growth—such as fava beans, cabbage, lettuce, turnip, wheat, radish, etc.—That completes their life cycle within 35 days. There are varieties of the genus *Brassica* that enable researchers to determine the germination rate, growth rate, seed yield, seed fertility, and other parameters in a short period. In fact, there is a current German project entitled "Biological Methods for Soil Remediation" that utilizes radish and oats to assess the degree of soil contamination [44].

Pollutant-Tolerant Plants (Plant Tolerance to Pollution)

The method of employing plants for the remediation of contaminated soils relies mostly on the plants' capacity to amass elevated amounts of hazardous chemicals in their tissues without disrupting their life cycle. Resistant plants—those adept at withstanding both organic and inorganic pollutants, neutralizing their toxic effects, and absorbing and sequestering contaminants—achieve this through mechanisms such as:

Binding of the element to the cell walls;
- Possession of membranes resistant to heavy metals;
- Exhibiting distinctive cellular activities that resist the pollutant, especially heavy metals;

• Possession of resistant enzymes that sequester the pollutant in one location (e.g., by accumulating heavy metals in the cell vacuoles);
• Chelation of elements via organic or inorganic bonds [32].

Biochemical processes also occur that help plants resist heavy metals. For example, the acid phosphatase ATPase present in the plasma membrane of root cells plays an important role in transforming pollutants in a way that eliminates their toxic effects within the plant [45].

The sequestration of excess concentrations of accumulated elements within the vacuoles of leaf cells is an effective strategy employed by plants to avoid the toxic effects of accumulated pollutants. Moreover, the accumulation of elements in the leaves followed by leaf shedding is considered one of the mechanisms by which plants may resist heavy metals. If a large quantity of leaves is shed, it indicates that these plants should not be used for the remediation of contaminated soils [46]).
Essentially, focus should be placed on three main axes for developing phytoremediation technology for contaminated lands, namely:
Improving the genetic traits of the plants used in phytoremediation: —such as the external morphology of the roots, root exudates, detoxification enzymes, and others.
Enhancing soil environmental: conditions from both physical and nutritional perspectives to create an ideal environment for the growth of the plants used in remediation. This also involves the addition of soil amendments to increase the availability of nutrients for plant uptake [47].
Managing agricultural operations: such as crop management, weed and disease control, and harvesting technology [48].

Examples of Aquatic Plants Used in the Bioremediation of Water and Soil Pollutants:
• Sargassum spp. and Ulva spp.
• Potamogeton pectinatus
• Myriophyllum spectrum
• Ceratophyllum demersum
• Potamogeton crisps
• Eichhornia crosspiece
• Phragmites Australias'

Biological Treatments for Organic and Inorganic Pollutants

Bioremediation of Petroleum Wastes (Tar) Using Wild Plants: Hegazy,[49] demonstrated through an experiment on tar-contaminated soil in Qatar on the Arabian Gulf coast that some wild plants—such as *Aizoon canariense, Anabasis satifera, Atrilex leucoclada, Fagonia indica, Caroxylon imbricatum, Senecio glaucus, Sporobolus arabicus, Suaeda aegyptiaca, and Zygophyllum qatarense*—can exhibit ideal Growth in this tar-polluted soil, where the tar concentration reaches up to 20% of the soil's weight. However, treating this soil with plants requires certain precautions, including consideration of the age of the contaminated site, the amount of solidified tar, the moisture content, the size of the area to be treated, the pattern of tar accumulation, and the surrounding climatic conditions such as temperature, light, rainfall, and others. Plant growth helps to aerate the soil and increase its organic matter content, and the presence of a small amount of tar enhances the water-holding capacity of sandy soils.
Bioremediation of Heavy Metals: Experiments have shown that some aquatic plants, such as Nile lotus and *Nakhshoush al-Hoot*, have the ability to absorb heavy metals from water and water-saturated soils. For example, Nile lotus is capable of absorbing manganese, copper, nickel, and lead, whereas *Nakhshoush al-Hoot* can absorb iron, manganese, and copper from the liquid wastes of factories [50]. Heavy metals are among the most dangerous pollutants because they do not degrade into simpler substances and can accumulate within the tissues of living organisms through transfer along the food chain. They are also among the most hazardous substances introduced into soil from various agricultural and industrial sources [51].

The phenomenon of heavy metal accumulation in plants has attracted significant research interest due to its important applications in phytoremediation. These plants can be exploited to extract pollutants (i.e., heavy metals) from soil and water by absorbing these elements from the soil solution and transferring them to the aboveground biomass. In addition, the technique of converting them into volatile compounds—known as phytovolatilization—is utilized. Moreover, some plants possess the ability to incorporate certain heavy metals into volatile compounds for their subsequent removal [52].

According to research, numerous plants are capable of extracting and accumulating heavy metals from contaminated areas. The optimal plant for this process should exhibit specific characteristics, including rapid growth, dense and deep root systems, large biomass, ease of harvest and cutting, and the ability to accumulate a diverse array of elements while tolerating high levels of those elements [53]. However, there are genetic variations among plant species in their capacity to withstand toxic concentrations of specific non-essential elements, including lead, cadmium, silver, mercury, and others.

Plant resistance to heavy metals is attributed to the following: Binding of the element to the cell walls. Presence of a membrane resistant to heavy metals. Enhanced cellular activity to eliminate heavy metals. Sequestration of heavy metals in a single location, such as their accumulation in cell vacuoles.

Dyes, pharmaceuticals, and agricultural chemicals receive primary attention due to the fact that 50% of the material utilized in the production of these substances is lost to nature as pollutants. During operation, testing, production residues, packaging, transportation, and excessive use, as well as through the compounds produced by the reaction of surfactants with the residues of these substances at each stage, this loss occurs in stages [54].

Other pollutants may have a very harmful biological effect on the health of humans and animals directly, such as residues from hospitals, homes, slaughterhouses, farms, galvanizing workshops, and smelters. These pollutants are distributed in the environment in three main compartments: air, water, and soil.

Biological treatment of rubber factory wastes In the 1980s in Malaysia, Nile lotus was used to reduce the pollution levels in the liquid wastes of rubber factories. Results have shown that after ten days of plant growth in these waters, there is a removal of 43% of total solids, 79% of suspended solids, 92% of the chemical oxygen demand (COD, i.e., the oxygen demand from organic sources), 98% of the biological oxygen demand (BOD), and 56% of the nitrogen content [55].

Biological treatment of palm oil mill effluents Nile lotus has also been used in Malaysia to treat palm oil mill effluents. Experiments have demonstrated that the pollutant levels decrease to less than one-quarter, provided that the plants are renewed every ten days. Additionally, research contributions from Egypt indicate that papyrus has the ability to cleanse the soil pollutants, especially heavy metals [56].

Benefits of using higher plants in purifying and remediating soil [57] The treatment period is lengthy, potentially lasting up to ten years. A significant amount of the plants used for soil remediation becomes unfit for use and must be disposed of safely, preventing the pollutants from re-entering the soil or water.

However, the presence of human and economic obstacles in recognizing the importance of sustaining the growth of these plants renders the soil or water unusable for a period of time, while huge sums of money are spent on treatment.

3. Conclusion

The present study reveals that phytoremediation is a safer method for removing environmental pollutants compared to mechanical methods or the use of certain substances that may also negatively impact the environment or pose risks to living organisms. In bioremediation, live green plants are used directly on the site or at the source of contamination, where they either eliminate contaminants or keep them in the soil. The contaminants progressively break down as these plants are grown in the polluted environment. This technology is more stable and effective than other mechanical approaches, and it is inexpensive and provides a cost-efficient way to remove a variety of environmental contaminants.

Plants can effectively eliminate contaminants, remediate contaminated environments, and extract them from water, soil, and air. Plants decompose organic contaminants and heavy metals, absorb them, stabilize them, and convert them into non-toxic compounds.

Pollutant uptake in plants first occurs in the roots, where several mechanisms help prevent toxicity during absorption. The roots provide a large surface area for pollutant absorption, making it possible to use larger trees for the remediation of groundwater contamination. This is due to the deep-root systems of trees, which extend significantly into the soil, making them more effective than smaller plants in pollutant removal.

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