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Phytoremediation of Oil Pollutants: Sustainable Soil and Water Techniques in Industrial Environments: A Review

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ABSTRACT

Oil contamination is one of the most significant environmental problems in recent times. By harnessing the ability of some plants to absorb and decompose petroleum hydrocarbons in water and soil, phytoremediation has become a low-cost, effective, and sustainable technique for removing these contaminants. This study investigated phytoremediation methods, the kinds of plants utilized, and the mechanisms between plants and contaminants, as well as an overview of research and development opportunities in this field and the practical and technical challenges facing it. It also assesses the potential of by means of local plants to remediate petroleum hydrocarbons present in wastewater and highlights successful field studies, especially in fields similar to Iraq. The study also provides many suggestions and treatments to improve this method and integrate it with other methods, such as biostimulation and bacterial support, to increase its effectiveness. The results support the idea that cleaning the petroleum refinery effluents in developing countries using plant treatment is a sustainable, practical, and inexpensive solution. By restoring the deteriorating areas and reducing dependence on expensive traditional technologies and risks, sustainable development goals can be achieved by adopting this technology. Phytoremediation can be considered a successful, effective, and inexpensive strategy for dealing with petroleum refinery wastewater pollution and restoring ecological balance through support for applied studies and research.

1. Introduction

The environment can be considered as one of the most important aspects of life[1]. However, industrial processes have recently posed an increasing and critical threat to it[2], especially in countries that produce and export oil[3], [4]. One of the most dangerous organic pollutants today is oil pollution, which is considered a major and critical threat to ecosystems[5]. Despite being the world's main source of energy and a vital and essential component of the global economy, oil also contributes significantly to the degradation of ecosystems, especially when it leaks or spills into soil or water, causing long-term pollution that is difficult to treat with known conventional methods [6], [7].

Iraq is considered one of the most important Arab countries and the most affected by these types of pollutants due to its vast oil reserves, massive oil facilities, and daily production lines, especially around oil fields, refineries, and pipelines[8]. According to respected environmental research, oil pollution endangers human and animal health and threatens biodiversity, causing a decline in biodiversity and soil fertility, and the

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accumulation of hazardous compounds in food chains[9]. The presence of petroleum effluents in wastewater poses an environmental concern since these organic petroleum hydrocarbons are toxic to aquatic and non-aquatic life. Several technologies are available for removing contamiation from wastewater, including electrochemical[10], membrane nanofiltration[11], adsorption via agricultural waste such as date palm fibres [12,13], sunflower husks[14,15], and Rice husk[16] and Phytoremediation [17]. Inadequate pollution control infrastructure and limited enforcement of contemporary environmental legislation exacerbate these problems and delay their resolution[18], [19,20]. Although traditional techniques for cleaning up pollution-such as burning, drilling, burying, and chemical treatment-may be somewhat successful in some cases, they are often costly and uneconomical, and may lead to secondary pollution. They also require sophisticated and expensive machinery and technologies, not to mention the risks to human and animal health and the environment[21,22]. Therefore, there is a need to identify alternative method effective, inexpensive, long -term, and environmentally friendly. One of the most well-known of these modern methods is Phytoremediation [17].

The utilize of specific types of plants that can absorb, identify, destroy and transform inorganic and organic contaminants from water and soil into less or harmless molecules are the basis of the biological processes identified as phytoremediation[23,24]. Plants perform this through complex biological processes such as internal decomposition, volatilization, and uptake through roots. It also cooperates with root microbes, which are necessary to enhance the efficiency of biological decomposition[24]. Phytoremediation has attracted increasing interest in recently because of its many benefits, including its ability to withstand costs compared to chemical and physical methods, compatibility with a variety of environments, ease of utilize, and the absence of additional contamination [25,26]. It is seen as an effective way to restore contaminated lands and also helps to improve the soil and fertility structure, which makes it a good choice for developing and poor countries that lack economic and technical resources and experiences[27]. Depending on the type of contamination and the type of plant utilized, several phytoremediation processes are utilized[28]. There are major categories in phytoremediation processes are included phytodegradation which plants use enzymes to destroy complex vehicles into simpler groups, phytoextraction is the process through which pollutants are absorbed and stored in vegetable tissues, rhizobiosis is the product of microbial activity in the root area, and phytofixation which prevents pollutants from moving and spreading by repairing them in the root area[29,30].

Choosing the appropriate plant species is the most important factor in phytoremediation[26]. These plants should preferably have a large biomass, strong, extensive roots, and the ability to interact with hydrocarbon-degrading microbes, as well as the ability to adapt to adverse environmental conditions[31,32]. Important examples of plants used in this field include reeds (Phragmites australis), palm trees, vetiver (Vetiveria zizanioides), poplars (Populus spp.), Nerium oleander (Nerium oleander L.) and other plant species that have proven effective in field restoration initiatives worldwide[24].

Microorganisms in the root zone also contribute significantly to the biodegradation process, improving the plant's ability to absorb and decompose pollutants[33]. According to experiments, the addition of biofertilizers containing specific bacterial species, such as Bacillus and Pseudomonas, can accelerate the decomposition process and improve the effectiveness of phytoremediation[34]. Phytoremediation has drawbacks despite these advantages[35]. In comparison to traditional procedures, it takes a comparatively longer time to produce good results, and its depth is limited, making it inefficient for treating contaminants present in groundwater or deep soil layers. Additionally, the efficacy of the system may be decreased by certain extremely toxic petroleum compounds that kill helpful microbes or prevent plant growth[36]. As a result, enhancing this technology necessitates a careful examination of the local ecology, the employment of a mix of native and genetically modified plants, and contemporary biotechnology[37].

Given the substantial growth of the oil and refining industry in Iraq, the use of phytoremediation may offer a novel environmental remedy for cleaning up oil-polluted sites, particularly in the oil-rich southern and northern areas like Basra and Kirkuk[38]. Reclaiming degraded lands and accomplishing sustainable development objectives pertaining to resource conservation and sensible use could be made possible by this method[39]. By reviewing biological mechanisms and field applications, analyzing the factors affecting their effectiveness, and highlighting the most notable local and international experiences in this field, this study aims to investigate the potential of phytoremediation of oil pollutants in soil. It will also present recommendations to support their use and development in oil-polluted environments in Iraq and similar countries.

1.1 Objectives

In order to demonstrate the efficacy of phytoremediation technology as a secure and bio-based approach to treating oil pollutants in soil, the study looks at the biological processes by which plants absorb and break down pollutants, finds appropriate plant species, and assesses the variables influencing this technology's effectiveness. An example of an environment affected by petroleum refinery wastewater pollution activity; it also emphasizes the extent of its ability to be applied in the Iraqi context. In addition, the study seeks to make useful suggestions to encourage the application of this technology in environmental reclamation initiatives.

2. Materials and methods

2.1 Crude oil components

Crude oil is a complex mixture of organic compounds that consist primarily of hydrocarbons, as well as varying amounts of compounds that contain elements such as heavy metals, oxygen, nitrogen, and sulfur. Its chemical composition varies depending on the geological source and the site of extraction, but its basic components can be classified as follows[40].

2.1.1 Hydrocarbons:

It represents the largest percentage of crude oil components and includes the following types[41]:

• **Paraffins or Alkanes**: These are the saturated compounds that consist of straight or branching carbon chains (such as heptane, pentane, ethane, and methane). These compounds make up a large part of fossil fuels and are used in gasoline and diesel production[42].

• **Naphthenes**: Saturated cyclic hydrocarbons, like cyclohexane and cyclopentane, frequently exist in heavy oils and have relatively strong combustion characteristics [43].

• **Aromatic Hydrocarbons**: Among the most dangerous materials present in petroleum compounds are molecules with a gasoline loop, such as benzene, xylene, and toluene, which have harmful effects on the environment and human health[44].

2.1.2 Non-Hydrocarbon Compounds:

• **Sulfur and its compounds**: These materials come in a variety of compounds, including hydrogen sulfide (H_2S), organosulfur compounds, and thiophene. Sulfur represents a big problem during the refining processes as a result of corrosion of equipment and environmental consequences[45].

• **Nitrogen**: These materials can be present as organic nitrogen compounds such as pyridine and quinoline. Their presence in petroleum affects the efficiency of the refining process and works as a measure of the era of petroleum reserves[46].

• **Oxygen**: These substances are found in trace amounts and are typically found as organic acids, phenols, or alcohols[47].

• **Heavy Metals**: For example, lead, nickel, vanadium, and iron are dissolved metals or organic complexes. When petroleum derivatives are burned or seep into the environment, these substances cause serious environmental problems.

• **Asphaltenes and Resins:** These are high-molecular-weight components found in greater quantities in heavy oils. They contribute to the viscosity of the oil and are responsible for deposit formation during transportation and storage[48].

2.2 Physical properties associated with the components

Understanding the components of crude oil is essential for determining appropriate treatment methods, whether in industrial refining or in the event of environmental contamination, as the nature of these compounds determines their hazardousness, toxicity, and the difficulty or ease of processing them using methods such as phytoremediation or bioremediation[49]. Figure (1) show remediation methods for contaminated soil with the crude oil spill, sediment and groundwater.

• **Density**: Varies depending on the proportion of asphaltene and heavy compounds[50].

• **Viscosity**: Increases with increasing proportions of heavy compounds such as resins[51].

• **Color and odor**: Affected by the presence of sulfur and aromatic compounds[52].

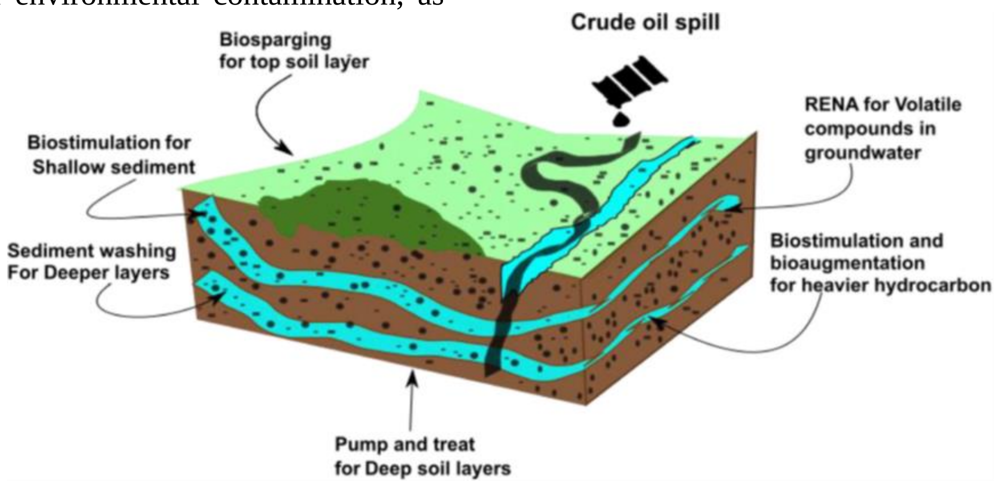

Figure (1): Remediation approaches for contaminated soil, sediment and groundwater [53].

2.3 Sources of oil pollution and its environmental impact

The sources of oil pollution are numerous, resulting from the continuous expansion of the petroleum industry and related activities. These can be classified into two main sources: exploration and extraction operations, where oil drilling and exploration lead to the leakage of crude oil into the soil and water; transportation and storage operations, which constitute a major source due to accidental incidents such as pipeline leaks, tank overturns, or tank explosions; and industrial and refining operations, which produce waste containing hydrocarbon compounds that may be discharged directly or indirectly into the environment. In addition, wars and natural disasters contribute to the increase in large-scale oil spills, as occurred in the Arabian Gulf region during the 1991 war[54,55].

In terms of environmental impacts, oil pollution is considered one of the most dangerous types of organic pollution, due to the complex nature of the hydrocarbon compounds that characterize oil, which include alkanes, polycyclic aromatic hydrocarbons (PAHs), and sulfur and nitrogen compounds. By decreasing soil permeability, eliminating beneficial microbes, and decreasing fertility, these compounds have a deleterious effect on soil . In addition, surface and groundwater are frequently contaminated with these substances, endangering aquatic life, associated ecosystems, and the balance of life[56]. Moreover, the vital accumulation of these detrimental compounds directly influences living organisms, such as animals and plants, and over time, it causes severe environmental imbalances. These influences can be transmitted to humans by means of food chains, which increases the risk of serious diseases such as chronic poisoning or cancer[57]. The choice of appropriate treatment methods depends on a comprehensive understanding of the reasons for this contamination and its influences on the environment. Consequently, there is a need to utilize sustainable and realistic solutions like phytoremediation, which uses the ability of plants and microbes associated with them to remove or reduce petroleum refinery wastewater pollutants in safe and natural ways[58].

2.4 Behavior of crude oil components in the environment

When the crude oil spill happens, the ingredients of the crude oil start to interact with several environmental factors, such as water, air, and soil. This reaction leads to a series of biological, physical, and chemical processes that determine the fate and the environmental behavior of these components. These processes are collectively known as the fate of oil in the environment and include evaporation, dissolution, adsorption, diffusion, oxidation, biodegradation, and sedimentation[59]. Figure (2) explains the crude petroleum oil spill impacts on the environment.

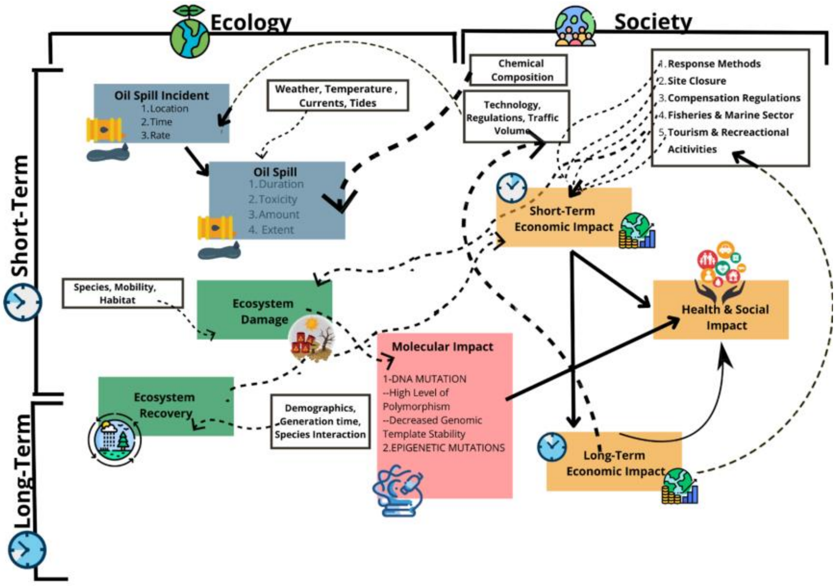

Figure (2): Crude petroleum oil spill impacts [60].

2.4.1. Evaporation:

Light alkanes (such as methane and pentane) and light aromatics (such as benzene) are among the first components to evaporate when oil is exposed to air, especially in hot conditions or when it leaks to the surface of water. This evaporation occurs over hours to days and reduces the total mass of the spilled oil, but it can release toxic air pollutants that pose a health risk[61].

2.4.2. Dissolution:

Some compounds that are partially soluble in water, such as sulfur and nitrogen compounds and light aromatic hydrocarbons, migrate from the petroleum mass to the surface or groundwater. These compounds are toxic to aquatic organisms and cause chronic toxic effects such as impaired growth or reproduction[62].

2.4.3. Adsorption:

Heavy compounds such as asphaltene and resins adhere to soil particles, especially in clay soils with high organic content. This binding reduces their mobility, but makes them more difficult to treat and prolongs their persistence in the environment[63].

2.4.4. Biodegradation:

Bacteria and fungi are effective agents in degrading some petroleum components, especially alkanes, converting them to less toxic compounds or to carbon dioxide and water. However, biodegradation is affected by many factors such as temperature, oxygen availability, soil or water type, and the presence of nutrients. Heavy aromatic compounds, however, are relatively resistant to biodegradation[64].

2.4.5. Oxidation:

Some petroleum components can be oxidized by atmospheric oxygen or ultraviolet radiation, leading to the formation of more polar and sometimes more toxic compounds. These compounds can contribute to the formation of surface films that impede gas exchange in water[65].

2.4.6. Sedimentation:

When oil interacts with suspended matter or sludge in water, heavy emulsions can form and settle to the bottom of rivers or lakes, resulting in long-term contamination that is difficult to address with conventional treatments[66].

Choosing the best treatment method requires an understanding of how the constituents of crude oil behave in the environment. For instance, pollutants that are soluble or adsorbed to the soil surface respond well to phytoremediation, whereas heavier contaminants necessitate a combination of chemical medium alteration and biostimulation [67].

3. Results and Discussion

3.1 The role of plants and their mechanisms in treating oil pollutants

Because of its low cost, beneficial effects on the environment, and capacity to restore damaged lands, phytoremediation is one of the most sustainable and successful bioremediation methods for eliminating oil pollutants from soil and the environment. This method depends on specific plant species' capacity to absorb, break down, stabilize, or volatilize pollutants from soil or water via a variety of physiological and biochemical processes, frequently in tandem with rhizosphere-dwelling microbe activity[68]. Oil pollution phytoremediation is depicted in Figure (3).

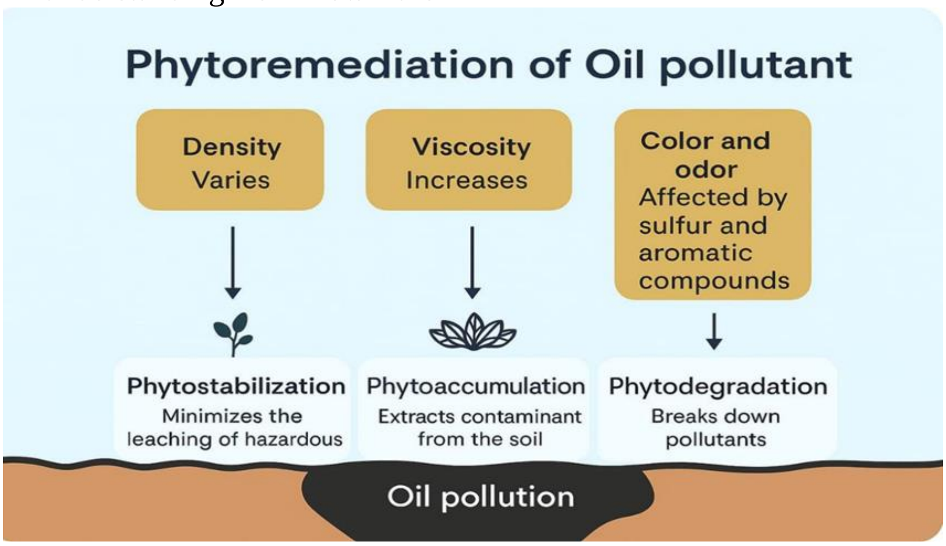

Figure (3): Phytoremediation of oil pollution

3.1.1. Phytoextraction:

In this mechanism, plants absorb oil compounds or their soluble components from the soil and transport them to their tissues, particularly the stems and leaves. This technique is typically used with transportable organic contaminants and is useful when the contaminant is physically removed from the site through harvesting and transporting the plant[69].

3.1.2. Phytovolatilization:

Some plants can absorb these pollutants, convert them into less harmful or harmless gases, and then release them into the atmosphere through their leaves. This is also often the case for moderate organic pollutants, such as some aromatic chemicals or organic solvents[70].

3.1.3 Phytostabilization:

Plants help fix contaminants in the soil and reduce their movement through partial absorption or attachment to nearby organic matter or roots. This process is critical to preventing contaminants from entering groundwater or being carried by surface water or wind[71].

3.1.4. Phytodegradation:

Plants produce enzymes within their cells or in the soil surrounding their roots to break down oil contaminants into less harmful compounds. These enzymes include peroxidases, monooxygenases, dioxygenases, and others. This mechanism is particularly effective against aromatic hydrocarbons[72]. This process is achieved through the interaction between roots and rhizosphere microbes. Organic materials secreted by plants (such as sugars and amino acids) promote the growth of bacteria and fungi capable of degrading petroleum compounds. This symbiotic association enhances the effectiveness of biodegradation of hazardous chemicals in soil[73].

The selection of the appropriate plant for each mechanism depends on several factors, including the type of contamination, the depth of the affected soil, soil type, climatic conditions, and the toxicity of the pollutants. Numerous studies have demonstrated the success of using plants such as reed (Phragmites australis), nigella, sunflower, poplar, and alfalfa in treating oil pollutants with high efficiency, especially when supplemented with biofertilizers or physical soil amendments[74]. Figure (4) explains the role of plants and their mechanisms in treating oil pollutants.

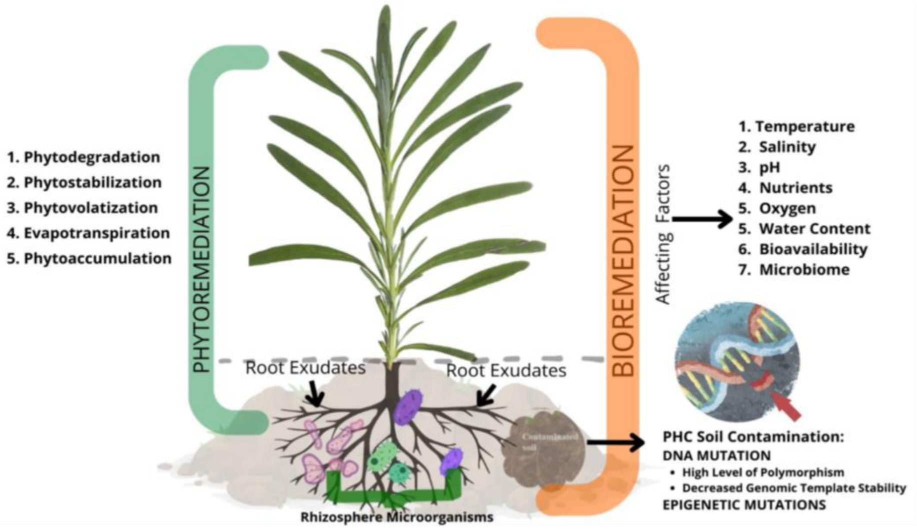

Figure (4): Role of plants and their mechanisms in treating oil pollutants[75].

3.2 Characteristics of plants suitable for phytoremediation

For plants to be effective in removing oil contaminants, they must possess the following characteristics[76]:

1. High tolerance to toxicity.
2. Rapid growth and high root density.
3. Effective root exudates that stimulate microbial activity.
4. Ability to thrive in poor or contaminated soils.
5. Ability to be harvested and processed after absorption.

Among the most important plants proven effective in phytoremediation of oil are sugarcane (Phragmites australis), sunflower (Helianthus annuus), alfalfa (Medicago sativa), mustard, corn, willow, and some local tree species such as poplar and arak[77]. Table (1) shows some types of plants used in plant treatment.

Table (1): phytoremediation of environmental pollutants

Type of contaminant	Common source	Phytoremediation method	Mechanism details	Examples of plants	Additional notes
Heavy metals such as (lead, mercury and cadmium)	Industrial waste, batteries, industrial wastewater	Phytoextraction	Absorption of minerals from the soil by the roots and their storage in the leaves and stems	(Helianthus annuus)، (Brassica juncea)	Effective in contaminated soil; requires several harvests to reduce concentrations[24,78].
Organic compounds such as pesticides and solvents	Agriculture, chemical waste, factory spills	Phytodegradation	Decomposition of organic compounds by plant enzymes or root-associated bacteria	(Salix spp.)، (Populus spp.)	Requires fast-growing plants and the ability to produce appropriate enzymes[79].
petroleum and hydrocarbons	Oil spills, gas station waste, petroleum industries	Rhizodegradation	Stimulates the growth of soil microbes around the roots to break down hydrocarbons.	(Phragmites australis)، Vetiver	Effective in wet and swampy environments[80].
Nitrates and phosphates	Agricultural fertilizers, wastewater, agricultural runoff	Phytofiltration	Absorption of nutrients from water through roots or submerged parts	(Typha spp)	Used in artificial wetland systems[81].
Radioactive materials such as uranium and cesium	Nuclear waste, leaks from nuclear power plants	Phytostabilization	Fixing radioactive materials in the soil and preventing their transfer through the roots	(Medicago sativa)	Reduces the spread of pollution but does not remove the pollutant[82].

3.3 Factors affecting the efficiency of phytoremediation

The efficiency of phytoremediation is affected by several factors, including [83]:

1. **Soil type:** Clay soils retain more contaminants than sandy soils, but they impede root growth.
2. **pH:** Affects the ability of contaminants to be absorbed and the activity of microorganisms.
3. **Temperature and humidity:** Control the rate of plant growth and biodegradation.
4. **Initial concentration of contaminants:** High concentrations may be toxic to plants.
5. **Presence of microorganisms:** The interaction between plants and microbes is a critical factor in root decomposition.

3.4 Successful Field Applications

3.4.1. The Iraqi Experience

Experiments conducted in oil-contaminated areas in Iraqi showed that reeds and nigella can reduce total oil concentrations in soil by up to 60-70% within 6 months, thanks to a combination of plant uptake and microbial decomposition[84].

3.4.2. The Nigerian Experience

In the Niger Delta, native plants such as mustard and willow were used in contaminated sites and demonstrated good pollution reduction efficiency, while improving soil properties and the growth of surrounding natural vegetation[85].

3.4.3. Experiments in South America

In Venezuela and Brazil, sunflowers and corn have been used to treat soils contaminated with aromatic hydrocarbons, recording reductions of up to 80% within a single growing season[86].

3.5 Challenges and limitations

Despite the advantages of phytoremediation, there are challenges that hinder its widespread application, including[87]: The long time required to achieve tangible results compared to physical and chemical treatments; The limited depth to which plants can penetrate, limiting their effectiveness in treating deep contamination; Plants are susceptible to excessive toxicity, which limits their growth or completely halts the biological process; Difficulty in disposing of contaminated plants after absorption, especially if they contain toxic compounds; The need for continuous environmental support (irrigation, ventilation, nutrients), especially in arid or saline areas[88].

3.6 Combining phytoremediation with other technologies

To overcome these challenges, it is recommended to combine phytoremediation with Biostimulation (adding nutrients or biostimulants to stimulate microorganisms), Bioaugmentation (adding microbial strains capable of degrading contaminants), and Physical pretreatment (such as soil tillage or pH adjustment to improve root permeability) [89].

3.7 Research and development prospects

Phytoremediation remains a rich field of research opportunities, including:
Genetic modification of plants to enhance their ability to tolerate pollution or produce more efficient enzymes. Studying the symbiotic relationship between plants and microbes to gain a deeper understanding of the mechanisms of root decomposition. Designing integrated treatment systems (wetlands) that combine plants, water, and natural filtration. Using local and environmentally adapted plants to reduce costs and increase efficiency [90].

4. Conclusions

Phytoremediation is one of the most promising environmental approaches to oil pollution remediation, due to its economic and environmental advantages, which have attracted the attention of researchers and decision-makers alike. Field and laboratory experiments around the world have demonstrated that plants, through a range of biological and biochemical mechanisms, are capable of mitigating or removing oil pollutants from soil and water effectively and sustainably. The success of phytoremediation depends on several interconnected mechanisms, including the direct absorption of hydrocarbons, enzymatic degradation within plant cells, and the important role played by microorganisms in the rhizosphere in decomposing contaminants with the help of root exudates. The foundation of remediation efficacy is the symbiotic interaction between microorganisms and plants, which also makes it possible to employ a combination of tactics to improve performance, like biostimulation or the deliberate introduction of helpful bacteria. The type of oil pollution and soil features or a water environment have a direct effect on the choice of appropriate species, which emphasizes the importance of comprehensive environmental evaluation before implementing the project. The limited depth to which plant roots can reach also poses a challenge in sites where contamination is deep. Furthermore, post-harvest management of contaminated plants presents an environmental challenge in itself, especially when toxic compounds accumulate in their tissues. Phytoremediation is particularly important in developing or environmentally fragile environments, where it represents a viable alternative to costly and complex treatments. Its effectiveness can be enhanced through integration with other technologies, such as bioremediation or physical remediation, which contribute to improving pollutant removal efficiency and reducing the time required for treatment. In light of the above, expanding the use of phytoremediation to address oil pollution requires building a local database of suitable plants, developing long-term monitoring and follow-up programs, and integrating this technology into national environmental policies. Supporting applied research in this field will also contribute to a better understanding of the complex physiological and microbial mechanisms underlying this process, paving the way for improved efficiency and expanded application.

5. Recommendations

1. Encourage local applied studies on plants adapted to environmental conditions in oil-contaminated areas, particularly in oil-producing countries such as Iraq, to identify the most efficient species in removing oil pollutants.
2. Encourage collaboration between researchers and the industrial sector, particularly oil companies, to implement pilot phytoremediation projects at production and transportation sites, and use their results as models for broader application.
3. Conduct periodic environmental assessments of treated sites to measure the long-term effectiveness of phytoremediation and ensure that sites are not recontaminated due to improper management of harvested plants or treated soil.
4. Raise community and environmental awareness of the importance of phytoremediation as a green solution with economic and environmental dimensions, to create a supportive environment for adopting this technology within environmental sustainability and agricultural development plans.

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