Bima Journal of Science and Technology, Vol. 8(4B) Jan, 2025 ISSN: 2536-6041

DOI: 10.56892/bima.v8i4B.1208

Phytoremediation of Crude Oil Pollution: A Mini Review

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ABSTRACT

Crude oil pollution severely impacts ecosystems, leading to biodiversity loss, water contamination, and soil degradation. These environmental disruptions pose significant risks to human and wildlife health while threatening long-term ecological balance. Phytoremediation, an eco-friendly and cost-effective strategy, utilizes plants to remediate crude oil-contaminated environments. Key mechanisms employed in this process include phytoextraction, phytovolatilization, phytotransformation, phytostabilization, and rhizodegradation. Recent innovations in biotechnology have further enhanced the effectiveness of phytoremediation through genetically modified (GM) plants engineered for improved pollutant uptake, degradation, and resilience to toxic conditions. This mini-review explores the principles, recent advancements, and potential applications of plant-based bioremediation strategies, highlighting their critical role in addressing crude oil pollution sustainably.

Keywords: Phytoremediation, Cride oil, Pollution, Genetically Modified

INTRODUCTION

The global population is growing exponentially, driving increased crude oil production and distribution to meet rising energy demands. Consequently, the incidence of oil spills worldwide and their devastating effects on humans and the environment is alarming. Soil pollution, a critical consequence of human activities, poses significant threats to ecosystems and human health (Naeem and Qazi, 2020). In Nigeria, many locations are contaminated with petroleum hydrocarbons (PHCs)—organic and inorganic compounds derived from crude oil. During oil exploration and industrial activities, these hydrocarbons are released into the environment and undergo chemical, physical, biological, and physicochemical interactions, spreading extensively (Truskewycz et al., 2019). The transformation processes alter the exposure, composition, and toxicity of these pollutants, further compounding their hazardous nature. PHCs are highly toxic and associated with carcinogenic, mutagenic, and teratogenic effects on living organisms (Yap et al., 2021).

Oil spillage remains a persistent challenge in Nigeria's oil-producing states, creating significant environmental management problems (Akindipe et al., 2023). Spilled crude oil and refined petroleum products, such as fuels and lubricants, contain toxic hydrocarbons, nitrogen-oxygen compounds, sulfur compounds, and heavy metals. These pollutants can cause acute and chronic harm to flora and fauna (Pal and Sen, 2024). Conventional remediation methods, including physical, thermal, chemical, and biological processes, are often limited by complexity, high costs, and potential for additional environmental damage (Tirumala et al., 2021).

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Phytoremediation has emerged as an integral component of bioremediation, utilizing plants to remove, contain, or transform contaminants in the environment. Certain plant species can thrive in polluted soils, extracting or degrading pollutants either independently or in association with microorganisms (Rotami and Azharpoor, 2019). Moreover, recent advancements in biotechnology have led to the development of genetically modified (GM) plants with enhanced capacities for pollutant uptake, degradation, and resilience in contaminated environments. These GM plants offer new possibilities for overcoming the limitations of conventional phytoremediation, making cleanup efforts more efficient and targeted.

Given the harmful impacts of crude oil pollution and the limitations of existing remediation methods, this study discusses the significance of phytoremediation, including the use of genetically modified plants, as a sustainable and effective solution for reducing crude oil pollution in the environment.

In this mini review, the authors performed an in-depth analysis of relevant literature sourced from Google Scholar, ResearchGate, and other online publications. By synthesizing information from various disciplines and cross-referencing multiple studies, they provide a comprehensive overview of the advantages, challenges, and practical applications of phytoremediation. The review also explores innovative technologies and real-world case studies, showcasing the potential of phytoremediation as an effective solution for mitigating crude oil pollution.

IMPACTS OF CRUDE OIL SPILLAGE ON THE ENVIRONMENT

Crude oil spillage has a vast negative impact on both the water and soil of the ecosystem. The life of aquatic and other valuable resources in lakes, rivers, and wetlands are threatened by oil spillage, such undesirable effects may cause toxicities in animals and other humans, including abnormal neuron development, genetic damage, physical deformities, as well as changes in biological activities such as feeding, reproduction, and migration (Bashir et al., 2020). Some animals are greatly affected by as little as 10 ml of oil slick, such as seabirds that suffer damage to their feather microstructure, which leads to lethally reduced thermoregulation (Tekeshita et al., 2021). The aquatic oil spill has been reported by many researchers to have an indirect effect on human health, consumption of food contaminated with hydrocarbon compounds in their tissues, and may result in bioaccumulation of contaminants along with their subsequent transfer through the food chain. Terrestrial and aquatic plants are exposed to both chemical and physical damage through oil spillage, lowering of carbon dioxide and temperature regulation due to fouling of plant leaves and the coating of plant roots, disrupting water and nutrient uptake by the plant roots (Kochhar and Gujral, 2020). The release of hydrocarbons leads to the inhibition of seed germination, a decrease in plant biomass production, and increased plant mortality. The soil's physical, biological, and chemical attributes are also negatively affected by oil spillage when the oil penetrates macro and micropores of the soil and thereby limiting water and air transport, which is highly essential for organic matter conversion (Kuhn et al., 2022).

The different heavy metals emit toxic substances, which have effects on human health and the environment. Environmental pollution by heavy metals has increased due to industrial development, and it is observed that many heavy metals are in higher concentration in those industrial areas. Heavy metals cannot be destroyed by degradation; as such, they have become a primary concern for environmental pollution. The remediation process of contaminated soils, groundwater, and surface water by heavy metals needs some methods to remove the metals from contaminated areas. Various methods have been used for removing pollutants from a contaminated environment. Soils that are contaminated with heavy metals can be treated by acid leaching, soil washing, physical or mechanical separation of the contaminant, electro-chemical treatment, electrokinetics, chemical treatment, thermal separation, and biochemical processes. These remediation techniques are costly, they take longer time, cause logistical problems, and have resulted in so much technical complexity. Therefore, an alternative solution is needed for heavy metal removal from the environment.

PHYTOREMEDIATION OF OIL SPILLAGE

Phytoremediation refers to the use of plants to reduce the concentrations of contaminants in the environment. It is a bioremediation technique that uses plants to clean up contaminated soil and water. Phytoremediation is a cost-effective, efficient, and environment-friendly technology that uses metal-accumulating plants to remove toxic metals, including radionuclides, as well as organic pollutants from contaminated soils and water (Ali et al., 2013). Phytoremediation is a sustainable and green process in which live plants are used for the clean-up of contaminants from the environment, making the environment non-toxic for human health and for plant growth.

PHYTOREMEDIATION AND ITS MECHANISMS

Phytoremediation consists of the Greek prefix ‘phyto’ which means ‘plant’ and the Latin root ‘medium’ which means ‘to correct or remove evil’. Many definitions of phytoremediation have been given by researchers. According to these definitions, (Khan *et al.,* 2022) made a general definition of phytoremediation as an emerging technology using selected plants to clean up the contaminated environment from hazardous contaminants to improve the environment quality. EPA (2000) noted that phytoremediation has been receiving attention lately as an innovative, cost-effective alternative to the more established treatment methods used at hazardous waste sites. Ali *et al.* (2020) called phytoremediation a ‘green technology’ because of its advantages as a cost effective, efficient, environment- and eco-friendly technology.

Phytotransformation

Phytotransformation and phytodegradation, which are different terms used for the same process, describe the metabolic reaction within the plant tissue. Organic and inorganic (atmospheric nitrogen and sulfur oxides) contaminants are either degraded/ transformed internally via metabolic processes or externally via extracellular enzymes (Kumari and Das, 2023). Phytotransformation processes include root-to-stem and leaf uptake and diffusion for transformation (Hussein *et al.* 2022). The phytotransformation mechanism has been proven to remediate multiple contaminants in soil and water, including petroleum hydrocarbons, pharmaceutical residuals, insecticides, pesticides, and surfactants (Kristanti *et al.,* 2023).

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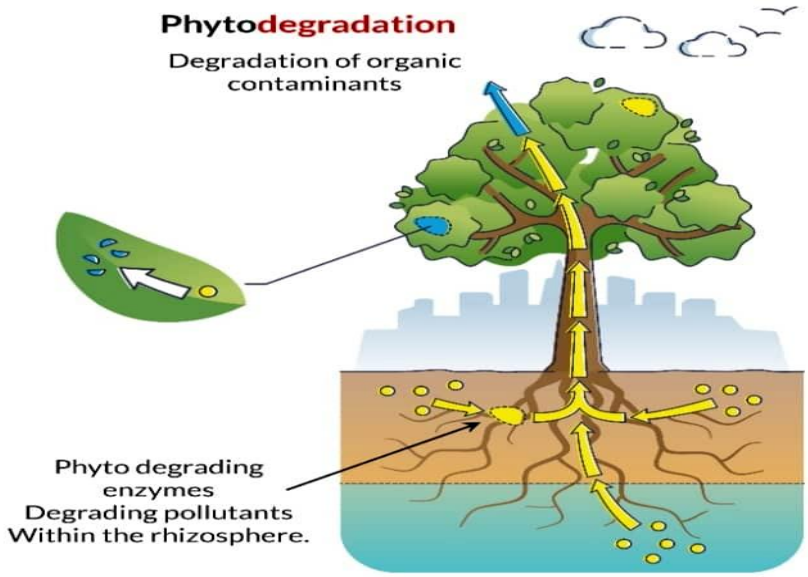

Figure 1: Diagram showing phytotransformation (phytodegradation) (Source: Tomar et al., 2020).

Phytostabilization

Phytostabilization involves the absorption and precipitation of pollutants such as organic compounds and heavy metals found in roots. The use of certain plant species to absorb and precipitate contaminants, generally metals, reduces their availabIlity, and in turn reduces their potential of contaminants to human exposure (Masindi and Muedi, 2018). This technique can be used to re-establish a vegetative cover at sites where natural vegetation is lacking due to high metal concentrations in surface soils. The linkage between plant metabolic process and soil physiochemical processes which is critical for nutrient flow from soil to plant aid in the precipitation and the reduction of movement of soil contaminants, preventing the pollution of other ecosystem compartments such as groundwater, bulk soil, and the food chain. Efficient uptake and accumulation of petroleum hydrocarbons by plants through phytostabilization might be used to prevent contaminants from migrating through erosion, leaching, and dispersion. This also helps incorporate organic pollutants into humic materials, which involves binding contaminants to the soil organic matter by plant enzymes or increasing soil organic matter content due to humification.

Phytovolatilization is the process by which plants or their associated microbes volatilize contaminants. This is followed by their translocation to stomata and, sometimes, to the bark and stem tissues to be released into the atmosphere (Limmer and Burken, 2016). This can occur in two ways, direct and indirect, In the presence of hydroxyl radicals, volatilized substances in the atmosphere might be damaged or oxidized. Examples of uses of phytovolatilization include volatilization of trichloroethylene by poplar trees, methyl tertiary butyl ether (MTBE) by weeping willows, and selenium by Indian mustard (Grzegorska *et al.,* 2020). Although this process has sparked concerns because of the risk of air pollution, it is not the primary dissipation pathway for most contaminants (Limmer and Burken, 2016).

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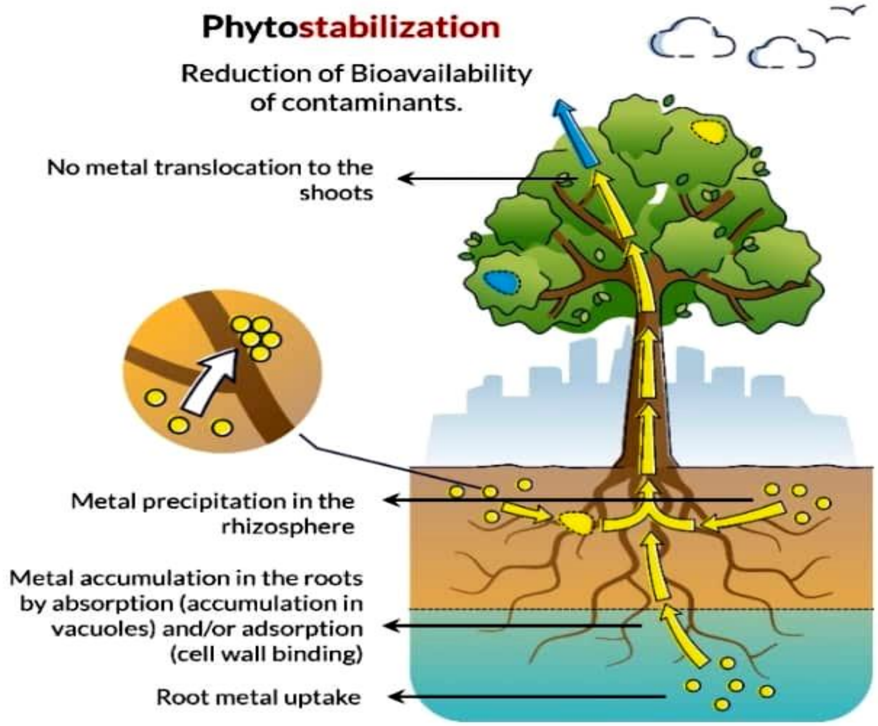

Figure 2: Diagram showing phytostabiloization process. Adapted from Wang and Chen, 2024)Phytovolatization.

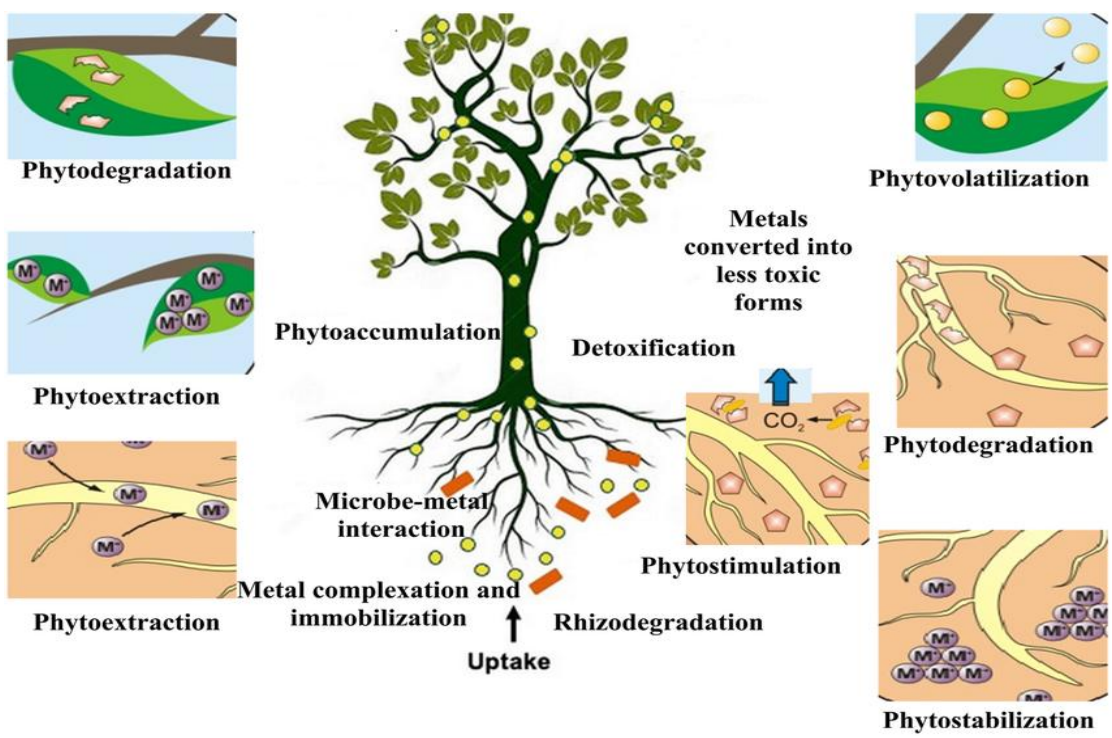

Figure 3: Diagram showing phytovolatization process. Adapted from Khanna et al., (2022).

Evapotranspiration

The process of evapotranspiration is a type of containment that uses the vaporization of water to control groundwater hydraulics. In arid and semi-arid locations, evapotranspiration by natural vegetation is effective, but it might also occur in different regions if climate and other conditions are taken into consideration (Kumar, 2023). Phreatophyte trees, such as poplar, eucalyptus, and river cedar, are examples of plants that take this approach, with deep roots that can transpire 200–1100 litres of water every day (James, 2022). Ogundola et al (2022) tested phytoremediation as a technology for environmental protection and for preventing the streaming of pollutants into hydrological systems and that the most effective plants for phytostabilization included Alfalfa, Salix, and Poplar species. They recommended that biomass taken from petroleum oil-contaminated sites should be composted or burned, whereas biomass taken from a mixture of contaminants (such as oil products and heavy metals) should be dried and transferred to a waste incineration facility.

Study by Elbasi (2021) shows that inoculating yellow lupine with the engineered endophyteBurkholderiacepacia resulted in improved phytoremediation potential of volatile organic pollutants and toxic metals from contaminated soils and groundwater by different mechanisms, including evapotranspiration. Because of the decreased enzyme activity involved in antioxidant defence in the roots, the experiment resulted in lower Ni and trichloroethylene (TCE) phytotoxicity. The success of phytoremediation in capturing the polluted water was directly proportional to the aquifer's horizontal conductivity, saturated thickness, and groundwater gradient. An important field of phytoremediation is remediating landfill leachate in municipal landfill sites. The water that has percolated through a solid and leached out some of the constituents is generated by the decomposition of landfilled organic waste and precipitation percolating through the waste material, which has to be treated before its exposure to the environment. Studies by Kumarathiliaka *et al.,* (2017) proved that willow plantations established on the restored cap of landfills can decrease leachate formation due to high evapotranspiration, whereas nutrients from the leachate can be taken up by willows or retained in the soil–plant system.

Phytoaccumulation

Also known as phytoextraction or phytomining, this refers to the removal or uptake of pollutants from the contaminated matrices and their translocation into the harvestable organs of plants (Suman *et al.,* 2018). This mechanism requires concentration or accumulation rather than breakdown, this strategy involves a plant- extracting inorganic pollutants from soil and water and translocating them to the plant shoots, followed by plant harvest for disposal or recycling. The process of uptake could be comparable to that of metals or nutrients necessary as co-factors for enzyme activity, for instance after intake, they are retained in vacuoles and to protect the plant from their damaging effects. Owing to their poor biomass formation, most hyperaccumulator plants are unsuitable for phytoremediation methods (Grzegórska *et al.,* 2020).

The rhizosphere activity, microbial biomass, and metabolism are all influenced by plant biomass production, particularly in the root system (Xiong *et al.,* 2021). The efficacy of accumulation is another key parameter in the selection of a good candidate for phytoremediation. Water plants, microalgae, root filters, and immobilized bacteria are all good alternatives for contaminated water (Yan *et al.,* 2020). The phytoremediation of radionuclides has become increasingly important because of their long half-life and their possible entrance into the food web after their accumulation in water and soil. There is a wide range of plant species that can remediate radionuclides with efficient phytoextraction potential (Yan *et al.,* 2021).

Advantages and Disadvantages of Phytoremediation

Advantages

1. **Eco-Friendly and Cost-Effective**: Phytoremediation is considered an environmentally friendly and cost-effective method for remediation of contaminated sites. According to Ali *et al*. (2020), it leverages the natural processes of plants to extract, sequester, and detoxify pollutants, making it a sustainable alternative to more invasive and expensive remediation techniques.
2. **Cleanup of Organic Pollutants**: This method is particularly effective in cleaning up organic pollutants such as petroleum hydrocarbons, pesticides, and industrial solvents. Plants such as poplar trees and grasses have been shown to absorb and break down these substances, thereby reducing environmental and health risks associated with contaminated soil and water (Gavrilescu, 2021) .
3. **Improvement of Soil Conditions and Erosion Prevention**: Phytoremediation not only removes pollutants but also improves soil structure and fertility. By stabilizing the soil with plant roots, it helps prevent erosion and promotes a healthier ecosystem. This dual benefit enhances the long-term sustainability of the remediated area (Garg and Paliwal, 2020).

Disadvantages

1. **Ineffectiveness in Low Temperatures**: One of the limitations of phytoremediation is its reduced effectiveness in low-temperature environments. Plant growth tends to slow down in colder climates, which can impede the uptake and metabolism of contaminants. This makes the process less reliable in temperate regions (Pi *et al*., 2021).

. **Air Contamination Risks**: Another significant disadvantage is the potential for air contamination. If plants used in phytoremediation are burned, the contaminants absorbed by the plants could be released into the atmosphere, posing a risk to air quality and public health (Agarwal *et al*, 2019).

INNOVATIVE TECHNOLOGIES FOR IMPROVING PHYTOREMEDIATION

. **Nanoparticles assisted phytoremediation**

The inclusion of nanoparticles (NPs) is a novel and inventive technique to improve the removal efficiency of heavy metals (Zhu *et al.,* 2019). Therefore, these particles have the ability to enhance phytoremediation through a variety of methods, such as: (a) interacting with heavy metals (HMs) by adsorption or redox processes, (b) inducing growth in plants, or (c) aiding in the phytoremediation of HMs (Song 2019). Through electrostatic adsorption, the chemical interaction demonstrated that nanoparticles can assist plants in stabilising heavy metals. NPs can stimulate plant development through rhizospheric bacteria and fungi. Numerous studies have shown how useful nanoparticles are for boosting phytoremediation.

In this regard, Khan and Bano (2016) observed that the combination of Ag nanoparticles (AgNPs) with plant growth-promoting rhizobacteria (PGPR) regulated the growth and phytoextraction potential of maize plants. It has been observed that adding nano-TiO_2 particles to Cd-polluted soil can improve the removal capability of Cd in soybean plants (Glycine max) (Singh and Lee 2016). Salicylic acid nanoparticles (SANPs) added

DOI: 10.56892/bima.v8i4B.1208

exogenously at an early stage of growth can enhance As phytoremediation using Isatis cappadocica (Souri *et al.,* 2017). Hussain *et al.* (2019) discovered that when magnesium oxide (MgO) nanoparticles and thidiazuron (TDZ) growth regulator are applied to radish (Raphanus sativus), the plant shows improved Pb accumulation and antioxidative response.

2. **Phytohormone assisted phytoremediation**

The process of phytoremediation with the assistance of plant growth regulators (PGRs) may enhance the accumulation of heavy metals (HMs) in plant tissues. There are four main types of plant hormones that have been found to be useful for this technique: gibberellins, auxins (IAA), cytokinins, and abscisic acid (ABA). Numerous studies have demonstrated that these phytohormones favourably affect the level of HM accumulation as well as plant growth and tolerance to HMs. It is commonly recognised that plants can avoid toxicity when exposed to heavy metals (HMs) by receiving exogenous phytohormone additions during the early stages of growth. One interesting method to increase Arabidopsis thaliana's resistance to Cd with only moderate effects is the addition of 0.05 M auxin (Chen *et al.,* 2024).Exogenous administration of 10 and 100 mM IAA in nutritional solution reduces the harmful effects of Trigonella foenum-graecum under Cd stress by blocking Cd absorption and controlling the ascorbate-glutathione cycle (Bashri and Prasad, 2016). According to Ji *et al.*, 2015, applying gibberellic acid 3 (GA3) at concentrations of 10, 100, and 1000 mgL^{-1} can greatly boost Solanum nigrum's biomass and phytoremediation effectiveness.

3. **Microbial assisted phytoremediation**

Utilising plant growth-promoting bacteria (PGPB), which can infiltrate the rhizospheric system and promote plant growth and mineral nutrition, is a key component of bioremediation. These microorganisms may break down hazardous substances or change them into less dangerous forms (Ullah *et al.,* 2015). It has been found that a number of PGPB increase plants' ability to absorb HMs through phytoremediation. By secreting various compounds including organic acids and siderophores (chelators), which lower the pH of the soil and increase the bioavailability of HMs, these bacteria are essential to the detoxification of heavy metals (Chen *et al.,* 2017).It has been documented that other bacteria release polymeric substances including glomalin and polysaccharides, which lessen the mobility of HMs and aid in their phytostabilization (Gujre *et al*., 2021). Certain PGPR are essential to the phytoremediation processes because they can boost plant detoxification rates, increase root secretion of enzymes that speed up pollutant destruction, or modify the pH of the soil, among other methods (Liu *et al.,* 2020). For instance, in soils contaminated with U and Pb, three bacterial endophytes—Pantoea stewartii ASI11, Enterobacter sp. HU38, and Microbacterium arborescens HU33—increase phytostabilization of Leptochloa fusca plants (Ahsan *et al*., 2017).

GENETICALLY MODIFIED PLANTS FOR PHYTOREMEDIATION

Genetically engineered plants are used as a promising tool for improving phytoremediation abilities. Although phytoremediation is considered ecologically and economically friendly, it has some limitations, including a low removal rate and inadequate tolerance of a plant to the pollutants (Ozyigit *et al.,* 2020). Developing transgenic plants with improved phytoremediation abilities should provide a solution to overcome the weakness of conventional plants that are used to remediate environmental pollutants (Gunarathne *et al.,* 2019). Genetically engineered plants for

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phytoremediation purposes were first developed to enhance the tolerance of toxic metals (Aken, 2008). The phytoremediation of toxic metals can be improved by overcoming the limitations of producing low plant biomass and the limited efficiency of particular plant species for phytoremediation (Suman *et al.,* 2018). The genes that are involved in the translocation, detoxification, acquisition, and sequestration of heavy metals have been identified in different organisms, including higher plant species, bacteria, and yeast. These genes can be transferred and over-expressed in plants that have phytoremediation potential. The produced transgenic plants can overexpress proteins that are important in pollutant assimilation and chelation, as well as membrane transport (Yang *et al.,* 2022).

The remediation process of organic pollutants can be improved by enhancing several mechanisms included in in-planta and ex-planta processes in the phytoremediation environment. The uptake of the organic pollutants and their subsequent diffusion to the plant organs, sorption and sequestration, or/and transformation are included as the in-planta processes, while the ex-planta processes include the degradation that occurs via the rhizospheres' microbial activity or the protein and co-factor excretion that results in non-specific activity (Hussain, *et al.,* 2022). The plants developed for organic pollution phytoremediation were modified to remediate halogenated and explosive pollutants. Currently, a wide variety of applications exist for transgenic plants in organic pollution phytoremediation, such as pesticides, explosives, organic hydrocarbons, phenolics, and organic solvents (Azab *et al.,* 2018). The transgenes present in these plants are responsible for enhancing plant tolerance to pollutants or increasing metabolic activity under pollution stress (Mishra *et al.,* 2020). The genetic manipulation of enzymes involved in phase I and phase II of xenobiotic metabolism is considered an important approach to enhancing the phytoremediation of organic pollutants. Cytochrome P450, as well as glutathione-S-transferase, are good enhancers of organic contaminants in phytoremediation. Other approaches target specific types of pollutants, such as the manipulation of laccases and peroxidases, to remediate phenolic compounds and nitroreductase or pentaerythritol tetranitrate reductase for the removal of TNT (Hussain *et al.,* 2018).

The expression of the human P450-1A2 gene enhanced plant tolerance and detoxification to the herbicide chlortolunon, and simazine in the transgenic Arabidopsis thaliana (Kebeish *et al.,* 2014; Azab *et al.,* 2016, 2018). Tolerance towards chlortoluron and isoproturon was reported by using ginseng-derived CYP736A12 and CYP76C1 genes that are overexpressed in Arabidopsis thaliana (Hofer *et al.,* 2014; Khanom *et al*., 2019). Other studies (Buono *et al.,* 2020; Mishra *et al.,* 2020) reported the enhancement of herbicide tolerance and metabolism in different plant species using cytochrome p450 transgenes. Plants and associated microorganisms in bioremediation Recent advancements in bioremediation technology and understanding have introduced the use of plants along with microbes for the remediation of petroleum hydrocarbons and other organic contaminants. This can be termed bioaugmentation-assisted phytoremediation (BAP) (Auti *et al.,* 2019).

The interactions of microbes with plant systems, both above ground and in the soil, are important for plant productivity and growth in natural ecosystems and agriculture. These interactions are significant for determining the organic pollutants' fate in the plant-soil system. The synergetic effect between the microbes in the rhizosphere and plants can notably

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increase the success of the remediation of petroleum hydrocarbons in the soil. Rhizosphere bacteria are known to be a heterogeneous group of bacteria associated with a root and on the surface of the roots that improve the quality and extent of plant growth in a direct or/and indirect way. It was reported by Dzionek *et al*. (2016) that the degradative potential of microbes found in the rhizosphere may be increased by plants in several ways, such as increases in PHC-degrading microbes, the densities of microbial population, the expression of catabolic genes, catabolic genes horizontal transfer, and enhancement of hydrophobic hydrocarbon bioavailability. Plants that secrete organic compounds can induce microbes to degrade PHC by different mechanisms, including efficient microorganism attachment on the plant surface, polluted soil aeration, and the availability of organic pollutants and nutrients transport, even though it was reported that plants rarely have the potential for effective bioremediation of PHC-polluted soils (Gkorezis *et al.,* 2016).Some petroleum hydrocarbon-degrading microbes associated with plant use, also known as plant growth-promoting rhizobacteria (PGPR), have several advantages, including the ability to invert transformation and reduce residual pollutant risks.

The plant–microbial system offers higher remediation efficiency than phytoremediation only. During bioremediation that combined biostimulation and phytoremediation mechanisms, the organic compounds secreted from plant roots enhanced microbial activity and PHCdegrading microbes; subsequently, the microbial mineralization of organic pollutants in contaminated soils was enhanced (Siles *et al.,* 2018). Plant roots, which are involved in water and nutrient uptake and anchorage, are biochemical units that regulate numerousplant–soil interactions, including mutualistic relationships with beneficial endogenous microbes such as mycorrhizae, rhizobia, endophytes, and PGPR. Plant exudation is the primary influence that affects PHC degradation in the rhizosphere. Various compounds are exuded by plant roots into the rhizosphere, such as organic acids, phenolics, amino acids, and sugars (Yang *et al.,* 2023). Plant roots secrete biochemical compounds that are divided into two categories based on their molecular weight: Low-molecular-weight compounds such as phenolics, amino acids, monosaccharides, and aromatic and aliphatic compounds; and high-molecular-weight compounds such as proteins and polysaccharides (Kumar and Goel, 2019).

Plant roots secrete organic acids, such as the intermediates of the citric acid cycle, including malonic, citric, oxalic, fumaric, malic, and succinic acids; these are involved in various processes such as PHC microbial degradation in the soil. The secreted organic acids change the rhizosphere's chemical composition, and as a result, the bioavailability of organic pollutants in soils is changed (Ni *et al.,* 2020). This process is either enhanced directly by changing the soil conditions, including the characteristics of the soil surface and the soil pH, or indirectly by promoting the indigenous PHC-degrading microbial communities. Some soil microbes can mineralize root exudates while being used as growth substrates, which can further act as cometabolites for the persistent PHC contaminant degradation (Correa-García *et al.,* 2018).

Several studies have demonstrated the potential of certain microbes and plant combinations for the enhancement of the PHC biodegradation process. The inoculation of PGPR in combination with arbuscular mycorrhizal fungi (AMF) in soil contaminated with petroleum hydrocarbons and planted with Avena sativa increased plant dry weight and stem height compared to uncontaminated soil. This combination increased the plant's

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tolerance to crude oil pollution by augmenting the activities of enzymes and decreasing the level of MDA. Further, they contributed to improving the soil quality by increasing the activities of the soil enzymes urease, dehydrogenase, and sucrase (Xun *et al.,* 2015). Similarly, Das and Kumar (2016) found that seeds of Withaniasomnifera primed with biosurfactant produced PGPR Pseudomonas sp. AJ15 produced plants characterized by high values of shoot and root length, carotenoids and chlorophyll pigments, and germination percentage under various levels of crude oil contamination compared to non-primed seeds.

CONCLUSION

Phytoremediation is an environmentally sustainable and cost-effective technology for addressing the challenges posed by crude oil pollution. This review has highlighted its potential as a green alternative to conventional remediation methods, such as thermal, mechanical, and chemical techniques, which are often expensive, energy-intensive, and harmful to ecosystems. By leveraging the natural abilities of plants to extract, degrade, stabilize, and volatilize contaminants, phytoremediation offers a non-invasive, in situ approach that not only cleans up oil-polluted environments but also improves soil quality and prevents erosion. Despite its numerous advantages, phytoremediation has limitations, including reduced effectiveness in low-temperature environments and the need for significant land areas. Furthermore, its efficiency depends on factors such as plant species selection, site characteristics, and the extent of contamination. As a result, further research is necessary to optimize phytoremediation strategies, address its limitations, and evaluate potential risks. By doing so, this eco-friendly technology can become a more reliable and effective solution for mitigating crude oil pollution in diverse environmental contexts.

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