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Research Progress on in-situ Remediation of Typical Heavy Metals in Petroleum Hydrocarbon-contaminated Soil Enrichment by Plants

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ABSTRACT

Petroleum hydrocarbon is one of the dangerous substances in the process of petroleum development, refining, processing, transportation, and production. In the related activities of the petroleum industry, the output is large, and improper treatment will cause pollution to the surrounding environment. It is an urgent problem to conduct harmless and resource treatment of petroleum hydrocarbon polluted soil. Plant enrichment, as an environmentally friendly and pollution-free technical means, has the advantages of low cost and small change to the soil environment and effectively solves the problems of excessive heavy metals in petroleum hydrocarbons through plant enrichment. In this paper, the development process of plant enrichment, remediation methods, and plant enrichment of typical heavy metals (Cd, Hg, Zn) in petroleum hydrocarbon-polluted soil were systematically introduced. Through investigation, the mechanism and influencing factors of plant enrichment of heavy metals in the presence of petroleum hydrocarbons were summarized and analyzed, and the possible development direction of plant enrichment technology in the future was prospected.

INTRODUCTION

In the process of petroleum development and processing, oily sludge mainly includes landing sludge, settling tank sludge, three-phase separator sludge, oil spill sludge from production accidents, etc. The composition is complex, including some hydrocarbon substances and heavy metals that are difficult to degrade (Qu et al. 2017, Chen et al. 2017, Zan et al. 2021, Ren et al. 2021). At present, some oil and gas fields in China have been subjected to different degrees of combined pollution of petroleum hydrocarbons and heavy metals. For example, the soil of a shale gas well in Changning contains two pollutants: petroleum hydrocarbons and heavy metals nickel (Ma et al. 2018). There are more than 10 kinds of heavy metal elements in the oil-polluted soil of the Yellow River Delta (Li 2019). These heavy metals are mainly in the form of compounds, which lead to the lack of available potassium, phosphorus, and other nutrient elements and their reduced availability, thus weakening the soil’s ability to supply crops (Jiang et al. 2021). The complex interaction with organic pollutants in the soil may change the form, solubility, and bioavailability of pollutants, thereby inhibiting or promoting each other’s repair efficiency (Freitas et al. 2016). Heavy metals and polycyclic aromatic hydrocarbons in petroleum are carcinogenic and mutagenic (Xu et al. 2012), posing a potential threat to human life and health (Yan et al. 2009, Wu et al. 2015). Therefore, the combined pollution of petroleum hydrocarbons and heavy metals has attracted great attention worldwide (Huang et al. 2016, Istrate et al. 2018).

Soil heavy metal remediation techniques include physical, chemical, and biological technologies. Among them, physical technologies include heat treatment (Khan et al. 2004), glass restoration (Zhang et al. 2022), guest soil and soil exchange (Ren & Liu 2021), etc. Chemical techniques include leaching (Chen et al. 2022), curing stabilization (Singh et al. 2020), electrokinetic repair (Gao et al. 2021), and Fenton oxidation (Xu et al. 2016). In the above techniques, Li et al. (2021) repaired soil contaminated by petroleum hydrocarbon and heavy metal cadmium complex by immobilizing microorganisms for 60 days, and the heavy metal Cd in soil changed from exchangeable and organically bound states to residual states. The degradation rate of petroleum hydrocarbons reached 51.25%. Xu Hongting et al. (2019) used persulfate as an oxidant. They controlled the cathodic solution pH=4 treatment to remove Cu, Zn, Pb, and Ni in the soil with an average removal rate of 13.6%, 17.3%, 12.3%, and 17.1%, respectively. The average removal rate of total petroleum hydrocarbons was 96.2%. Although the repair efficiency of physical and chemical technology can reach 70%-90% (Yang et al. 2019, Li et al. 2020, Pan et al. 2021), it is also affected by other factors such as pH value, Zeta potential, and chemical properties, which are easy to destroy the physical and chemical properties of soil and cause secondary pollution (Hu et al. 2017, Gidudu & Chhirwa 2020, Diksha et al. 2022). Bioremediation is to remove soil pollutants through the ability of organisms to decompose toxic and harmful substances without changing the existing physical and chemical properties of soil (Ren & Liu 2021). These include phytoremediation technology (Liu et al. 2022), microbial remediation technology (Chishti et al. 2013), and animal remediation technology (Zhang et al. 2022). Among them, microorganisms have poor genetic stability and are prone to variation, and generally cannot remove all pollutants, and specific microorganisms can only degrade specific chemical substances. Once the state of the compound changes, it may not be degraded by the same microbial enzyme. In practical application, pollutants in soil have different forms and may be unstable. The adsorption and accumulation capacity of microorganisms for heavy metals is limited, and they have to compete with indigenous strains and are significantly affected by the environment (Xia 2019). The pollutants absorbed by animals during restoration may be released into the environment due to metabolism or death (Feng 2019), so phytoremediation technology has become one of the most popular technologies at present.

Phytoremediation refers to the use of plants to extract, fix, and degrade indigenous and foreign heavy metals in soil (USEPA 2000). To a certain extent, it makes up for the lack of microorganisms affected by climate and geological conditions and the low concentration of heavy metals in animals (Zhou et al. 2022). There are five main ways for phytoremediation of contaminated soil: plant extraction, plant volatilization, plant stabilization, root filtration, and plant degradation (Ye 2021). Phytoremediation techniques are shown in Table 1, and heavy metal remediation pathways are shown in Fig 1. Among them, plant extraction, plant stabilization, and root filtration are also collectively referred to as plant enrichment (Chen et al. 2013), which refers to the methods of fixing heavy metals on the surface of roots or absorbing them into the body and storing them in leaves, so as to gradually reduce or even eliminate the content of heavy metals in soil. As early as the 19th century, Baker et al. (1990) found that the distribution of *Alyssum bertolonii* in soil was significantly correlated with the contents of Ni, Cd, and Zn in soil, indicating the possibility of plant enrichment (Ingrouille & Smirnoff 1986). In the 1970s, relevant studies in China (Brooks et al. 1977) also used *Elsholtzia harchowensis* Sun distributed in copper mining areas of Anhui Province and parts of the middle and lower reaches of Hubei Province as an indicator plant for mineral exploration to further prove the existence of plant enrichment. Since then, studies on plant enrichment have gradually increased, and as a technical means to control contaminated soil, experimental studies, and field applications have been carried out in agriculture, petroleum, and other fields. Due to its improved plant tolerance and good environmental protection, it has attracted wide attention in recent years (Wei & Chen 2001, Shen 2012, Yao et al. 2019, Liu 2019, Mazeed et al. 2020, Yang et al. 2021). At present, researches on phytoremediation mainly focus on the soil surrounding mines and farmlands (Wang et al. 2018, Zhao et al. 2023), while there are few reports on heavy metals in oil-polluted soil because petroleum pollutants are easy to form mucous membranes on the surface of plant roots, hinder plant root respiration and nutrient absorption, and even cause root rot and plant death in severe cases. This affects the survival rate of plants (Luo 2022). Oil pollutants also significantly changed the original carbon, nitrogen, and phosphorus ratio of soil, increasing soil pH value and a significant decrease in organic matter content (Teng et al. 2015), thus changing the vertical distribution of soil nutrients and affecting the normal life activities of plants. In the oilfield site with serious soil heavy metal pollution, the detection rate and excess rate of heavy metals Cd and Zn are high (Tao 2000), the volatility of mercury (Hg) and the activity of exchangeable mercury in the soil are high, which are the three metals with serious pollution problems. However, in the process of phytoremediation of heavy metals, the interaction between petroleum hydrocarbons and heavy metals is still unknown (Li et al. 2012, Li et al. 2019, Ezekiel et al. 2021, Gong et al. 2022, Guo et al. 2022). Therefore, there is still a lot of room for the application of phytoremediation technology in the remediation of heavy metals in oil-contaminated soil.

In summary, aiming at the pollution problem of typical heavy metals (Cd, Hg, Zn) in the soil of crudely polluted sites, this paper systematically introduced the research progress of remediation of typical heavy metals in the soil of crudely polluted sites by plant enrichment and prospected the possible research development direction.

PLANT ENRICHMENT OF TYPICAL HEAVY METALS

In 1977, Brooks first proposed the concept of hyperaccumulator (Brooks et al. 1977), which refers to plants growing in the natural environment with dry weight Ni content exceeding 1000 $mg \cdot kg^{-1}$. With the deepening of research, American scientist Chaney et al. proposed the idea of plant enrichment of heavy metals in soil in 1983, and people gradually shifted the treatment of heavy metal pollution to the restoration of hyperaccumulators (Guo et al. 2022). Although the concept of hyperaccumulator has been proposed and widely used for more than 40 years, there are still many controversies about its evaluation methods. The most common evaluation methods for hyperaccumulators have two aspects. On the one hand, it means that the absorption of heavy metals by the above-ground parts of plants is 100 times higher than that of ordinary plants.

On the other hand, plants with BCF (Bioconcentration Factors) greater than 1 or TF (Translocation Factor) greater than 1 will not affect normal life activities (Zeng et al. 2019). In the past two decades, nearly 70 species of heavy metal hyperaccumulators have been discovered in China, which have strong root absorption, transfer, and leaf detoxification fixation abilities (Cui & Li 2016, Huang et al. 2020). It is mainly distributed in the southern region and is relatively rare in the cold regions in the north. Most hyperaccumulators grow in metal mining areas where soil nutrients are scarce (An et al. 2015). Most of them are herbaceous plants, while a few are trees and shrubs (Guo et al. 2022). The

Table 1: Characteristics of phytoremediation.

Phytoremediation technology	Repair pathway	Mainly repair heavy metal types	Reference
Phytoextraction	Heavy metals are transferred through plant roots to plant stems and leaves and harvesting stems and leaves remove soil heavy metals. Fast growth, large biomass, strong resistance to disease, strong adaptability to the environment.	Pb, Cd, Ni, Cu, Cr, Hg, Zn, etc.	(Luo et al. 2020)
phytovolatilization	Plant roots release chemicals that react with heavy metals, or plants convert absorbed solid or liquid heavy metal compounds into gases that are released into the atmosphere.	Hg, Se, As, etc.	(Liu et al. 2019)
Phytostabilization	Plant roots absorb heavy metals in the soil, weaken the flow and migration capacity of heavy metals in the soil so that they are not used for biological use, and reduce the environmental pollution caused by heavy metals entering the groundwater.	As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, etc.	(Ye 2021)
Phytofiltration	When the root system changes the rhizosphere environment of plants, the root system will secrete organic acids to change the form of heavy metals. Cadmium phosphate, zinc phosphate, and lead sulfate precipitate in root exudates to resist the toxicity of heavy metals. Insoluble phosphorus is the main form of extracellular metal precipitation.	As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, etc.	(Salt et al. 1995)
Phytodegradation	Plant roots and related microorganisms are used to degrade pollutants in soil. Microorganisms change the physicochemical properties of heavy metals to affect their migration and transformation and reduce the content of heavy metals.	As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, etc.	(Sabreena et al. 2022)

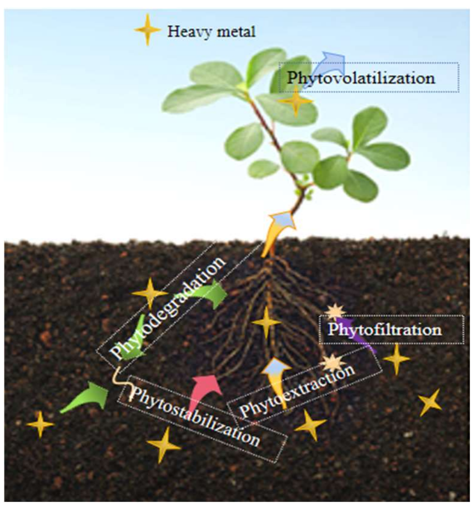

Fig. 1: Heavy metal remediation pathway.

Table 2: Related characteristics of Some hyperaccumulation plants.

Plant name	Sort	Repair metal	Repair effect/ground metal content	Reference
Chaetomitriopsis glaucocarpa	Herb	Zn	BCF>1	(Sun et al. 2018)
Hedwigia ciliata Ehrh. ex P. Beauv.				(Sun et al. 2018)
Sedum alfredii			19674 mg·kg^{-1}	(Long et al. 2002)
Arabis paniculate			77442 mg·kg^{-1}	(Tang et al. 2005)
Potentilla griffithii velutina			27600 mg·kg^{-1}	(Du 2005)
Picris divaricate			12472 mg·kg^{-1}	(Tang et al. 2005)
Sedum plumbizincicola			9609 mg·kg^{-1}	(Wu et al. 2012)
Symphytum officinale			17795 mg·kg^{-1}	(Zhang et al.2016)
Brassica juncea			18823 mg·kg^{-1}	(Zhang et al.2016)
Beta vulgaris cicla			159.79 mg·kg^{-1}	(Li et al. 2007)
Cardamine circaeoides			550 mg·kg^{-1}	(Liu et al. 2018)
Mirabilis jalapa			539.87 mg·kg^{-1}	(Zhou & Liu 2006)
Amaranthus tricolor			212 mg·kg^{-1}	(Fan 2007)
Euphobia thymifolia			202.086 mg·kg^{-1}	(Liu et al. 2006)
Emilia jaranica			404.23 mg·kg^{-1}	(Wang 2008)
Bidens pilosa			119.1 mg·kg^{-1}	(Sun et al. 2009)
Sonchus asper			387.5 mg·kg^{-1}	(Li et al. 2008)
Tagetes erecta			345.75 mg·kg^{-1}	(Lin 2008)
Artemisia argyi			105.59 mg·kg^{-1}	(Li et al. 2008)
Iva xanthifolia			474.30 mg·kg^{-1}	(Zhao et al. 2010)
Erigeron annuus			159.6 mg·kg^{-1}	(Cheng et al. 2010)
Cardamine hupingshanensis			131 mg·kg^{-1}	(Bai & Li 2012)
Sigesbeckia orientalis			192.92 mg·kg^{-1}	(Zhang et al. 2013)
Youngia erythrocarpa			317.87 mg·kg^{-1}	(Ning 2014)
Emilia sonchifolia			114.5 mg·kg^{-1}	(Zhou et al. 2014)
Galinsoga parviflora			205.62 mg·kg^{-1}	(Jin 2014)
Ageratum conyzoides			121.50 mg·kg^{-1}	(Sun et al. 2015)
Chenopodium ficifolium			179.73 mg·kg^{-1}	(Zhang et al. 2016)
Vinca major			190.82 mg·kg^{-1}	(Zhang et al. 2016)
Lolium perenne L.			BCF>1	(Jing et al. 2019a)
Sonneratia apetala Buchanan-Hamilton				(Peng et al. 2020)
Phytolacca americana L.		Hg		(Lu et al. 2004)
Euphorbia esula L.			35.1 mg·kg^{-1}	(Wang & Yi 2010)
Solanum nigrum		Cd	101.1 mg·kg^{-1}	(Wei et al. 2004)
Viola lucent			4825 mg·kg^{-1}	(Liu et al. 2003)
Lantana camara	Shurb		105.91 mg·kg^{-1}	(Sun et al. 2009)
Lonicera japonica			300 mg·kg^{-1}	(Liu et al. 2013)
Averrhoa carambola	Arbor		615 mg·kg^{-1}	(Lin 2010)

most typical hyperaccumulator in zinc-contaminated soil is *Sedum alfredii* (Zhou et al. 2021), *Solanum nigrum* (Wei et al. 2004), and *Viola lucens* (Liu et al. 2003) can be used as hyperaccumulators in cadmium-contaminated soil. *Euphorbia esula* L. can be used as a hyperaccumulator in mercury-contaminated soil (Wang & Yi 2010). The related characteristics of other hyperaccumulator plants are shown in Table 2. With the continuous breakthrough in the research of hyperaccumulator plants, a variety of hyperaccumulator plants that enrich typical heavy metals have been discovered and should be used in experiments and markets.

Cadmium Enrichment

At present, there are more than 40 kinds of plants that can repair cadmium-contaminated soil, among which more than 10 species of hyperaccumulator plants (Shi et al. 2015, Wang et al. 2016, Jale et al. 2018). Researchers (Zhang et al. 2022) found that *Acacia auriculiformis A. Cunn. ex Benth.* had strong cadmium resistance to Cd under the condition of increasing CO_2 and N content. Compared with Cd alone, *Syzygium hainanense* Chang et Miau increased plant biomass more than double and decreased Cd concentration in leaves. This is because CO_2 and N offset the adverse effects of cadmium on the biomass of *C. hainanensis* by increasing the photosynthetic rate, N concentration, and efficiency of the stem water transport network. In addition to the two plants mentioned above, *Cinnamomum camphora* (L.) Presl and *Castanopsis hystrix* Hook respectively significantly increased the cadmium ion concentration in leaves under the same conditions compared with cadmium content alone (Zang et al. 2021). They were 162.1% and 338.0%, respectively, indicating that plants have species-specific ability to repair cadmium pollution. Chen et al. (2021) combined three consecutive crops of cabbage, ryegrass, and cabbage with two kinds of biochar (PBC, Poplar bark biochar) and thiourea-modified poplar bark biochar (TPBC, thiourea-modified poplar bark biochar)was used to repair CD-contaminated soil in situ. Compared with the control group, the residual cadmium in soil increased by 75.75%, and the cadmium in a weak acid-soluble state decreased by 160.62%. The combined remediation of biochar and fast-growing plants can reduce the bioavailability of cadmium and also overcome the problem of low efficiency and a long time of in-situ remediation.

Mercury Enrichment

At present, there are more than 20 species of hyperaccumulators that can repair mercury-contaminated soil (Shi et al. 2015). The bioenrichment coefficient and transport coefficient of *Pteris vittate*, *Miscanthus sinensis* and *Ipomoea nil* were all greater than 1. However, some research results are limited to polluted soil with medium and low concentrations. Wu et al. (2022) found that the content and distribution of heavy metals in sediments of the Pearl River Estuary tend to be consistent with oil pollution, and the total mercury content in sediments is 0.104 $mg{\cdot}kg^{-1}$. Mercury in soil mostly exists in residual and organic bonded states. However, exchangeable mercury accounts for 0.04%, but this part of mercury has high activity, and it is easy to form complex mercury with sulfides in soil and combine mercury with organic matter (Zhao et al. 2014). The physical and chemical properties of soil determine the existence form of mercury. In soil with pH<7, mercury is the most sensitive to organic matter, and in alkaline soil, mercury is mainly absorbed by clay minerals (Li et al. 2018, Jia et al. 2020). Researchers (Aleksandra et al. 2008) found that *Salix viminalis* E. L. Wolf absorbs and distributes mercury in a plant-stable manner, preferentially binding mercury in the cell wall of the outer part of the cortex and central cylinder and in the thin-walled nucleus, with the highest mercury content in the roots and maintaining a rich microbial population in the rhizosphere. However, the root system of *Artemisia salix* is mainly distributed in the upper layer of the soil, polluted by mercury, which was unfavorable to the stability of the soil.

Zinc Enrichment

At present, there are more than 20 species of hyperaccumulators that can repair zinc-contaminated soil, distributed in 4 to 6 families (Konrad et al. 2018). Zou Yanmei et al. (2019) found through plant extraction that the enrichment coefficient of *Phragmites australis* for heavy metals in polluted soil with a mass ratio of total petroleum hydrocarbons less than 200 $mg{\cdot}kg^{-1}$ was greater than 1, which was because of the low concentration of petroleum hydrocarbons as a carbon source improved the respiration and transpiration of the reed. Then, the heavy metals migrate to the rhizosphere surface with water to promote their absorption in the roots. However, when the mass ratio of total petroleum hydrocarbon in the soil is greater than 410 $mg{\cdot}kg^{-1}$, macromolecules with higher hydrophobicity and greater viscosity in petroleum will adsorb on the surface of reed roots, which will reduce respiration and transpiration. The heavy metal enrichment ability will decrease. This is consistent with the findings of Li (2019). Yu et al. (2022) found that *Bidens pilosa* L. and *Xanthium sibiricum* Patrin ex Widder not only showed better metal extraction ability but also showed higher sprout biomass after repeated extraction of plants. The extractable lead, cadmium, and zinc contents of diethylenetriamine pentaacetic acid (DTPA) in plant rhizosphere soil were decreased. Foreign researchers (Peter et al. 2015) evaluated the Zn repair potential of *Acalypha wilkesiana* Mull. Arg. by setting gradient experiments, and found that pH, phosphorus, and water content of polluted soil repaired by *Acalypha wilkesiana* increased, nitrogen and organic carbon content decreased, and the plants accumulated a large amount of zinc in stems and leaves compared with the roots. By evaluating the bioenrichment coefficient (BCF) and transport coefficient (TF), zinc levels in roots and stems indicate that more bioavailable zinc pools are transferred from roots to leaves and stems, which can be used as plants to repair zinc-contaminated soil.

ENRICHMENT MECHANISM

The enrichment of heavy metals by plants in the presence of petroleum hydrocarbons in soil depends on the effects of plant root exudes on soil and rhizosphere microorganisms (Wang & Wu 2021, Wang et al. 2022). Root exudates refer to the general term of organic compounds released by some plants to the rhizosphere environment through their roots during the growth and development process (Xue et al. 2017). At present, more than 200 root exudates, including sugars, organic acids, enzymes, auxin, and amino acids, are released from different parts of plant roots into the soil environment, which can provide carbon and nitrogen sources required for microbial activities, increase the activity of rhizosphere microorganisms by up to 100 times, and improve the phenomenon of reduced diversity of soil bacteria caused by heavy metals (Ali et al. 2013, He et al. 2020). Under the stimulation of heavy metals, plants usually secrete a large number of organic acids with low molecular weight, such as citric acid and oxalic acid (Carballeira et al. 2016), which activate the insoluble heavy metals in soil and change the presence state or REDOX state of organic pollutants in the environment through reduction, acidification, and complexation, to reduce the toxicity of organic matter (Wu et al. 2018). Reduce the toxicity of organic pollutants to plants, improve the tolerance of plants, and promote the absorption, transfer, and enrichment of organic pollutants by plants (Niu et al. 2009, ar et al. 2012). Rhizosphere microbial effect refers to the use of a large number of rhizosphere soil microorganisms (including bacteria, fungi, actinomyces, etc.) to affect the toxicity, morphology, and biological availability of soil pollutants through various modes of action (Xing et al. 2004, Shinjini et al. 2014, Li et al. 2016). Root exudates are carriers of material, energy, and information exchange between plants and soil microorganisms, and plant rhizosphere microorganisms are effective proof that root exudates promote rhizosphere microflora changes. Plant roots can provide nutrients such as amino acids, vitamins, and enzymes required by microorganisms. Nutrients (Compant et al. 2009) also significantly stimulate soil enzyme reactions, such as terpenes, phenols, and organic acids (Jean-Patrick et al. 2012), which will affect the soil microbial community structure and increase the content of organic matter in rhizosphere soil. It can change the adsorption capacity of rhizosphere soil to organic pollutants, significantly improve the activity of rhizosphere microorganisms, and indirectly promote the degradation of organic pollutants by rhizosphere microorganisms. Rhizosphere microorganisms can consume organic matter and mineral nutrients in root exudates, change the type and quantity of root exudates, form a concentration gradient in the rhizosphere region, and directly promote the release of root exudates (Canarini et al. 2019). The mechanism of phytoremediation of heavy metals is shown in Fig. 2. Therefore, the interaction between root exudes and rhizosphere microorganisms plays a positive role in the enrichment of heavy metals.

INFLUENCING FACTORS

Temperature

Temperature is one of the important factors in maintaining normal plant growth, and it also affects the physicochemical properties of petroleum hydrocarbon pollutants. At low temperatures, the viscosity of petroleum hydrocarbons increases, while the volatility of toxic and low molecular weight petroleum hydrocarbons decreases, resulting in slow degradation of plants and soil microorganisms (Mar 1975, Foght et al. 1996, Ajona & Vasanthi 2021). Although plant degradation of petroleum hydrocarbon pollutants has the

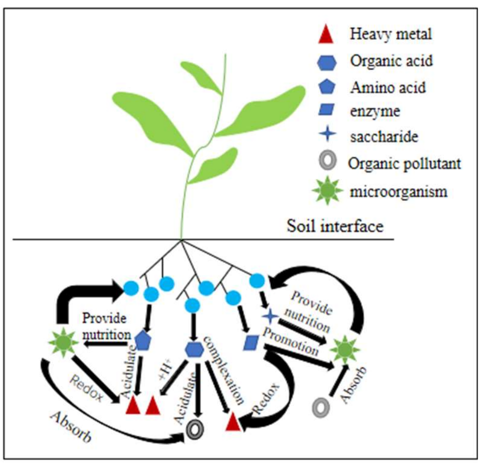

Fig. 2: Mechanism of phytoremediation of heavy metals.

highest degradation rate in the range of 30-40°C (Bartha 1984, Cooney 1984), the degradation rate usually decreases with the decrease in temperature. Higher temperatures increase the solubility of petroleum hydrocarbons, reduce viscosity, and transfer long-chain normal alkanes from the solid phase to the water phase (Jackie et al. 2006, OkohAnthony 2006).

Temperature also affects the ability of plants to accumulate heavy metals by affecting the growth and development of plants and biomass. Different plants have different requirements for temperature. When the temperature is suitable, the growth and metabolism of aquatic plants are vigorous, and the enrichment ability of heavy metal ions is also enhanced accordingly. Experimental studies have shown (Pan & He 2006, He et al. 2022) that *Eichhornia crassipes* stop growing at 5℃, start growing at 13℃, and grow faster above 25℃. At that time, it has a strong heavy metal enrichment ability, and at 30℃, it grows fastest, at which time it has the strongest enrichment ability.

Soil pH

pH value is the main factor affecting the enrichment of heavy metals in plants. Depending on the nature of the heavy metal and the environment in which it exists, changing the pH of the environment can alter the bioavailability of the heavy metal. Generally, lowering the soil pH will increase the heavy metal content in the soil solution. In the living environment of plants, most heavy metals exist in insoluble states, and their solubility is controlled by pH value. Heavy metals precipitate with the increase of pH value in the environment, thus affecting the absorption and utilization of plants (Fang et al. 2022). When the pH value of the plant's living environment is lower than 6, the metal does not easily form hydroxide precipitation, and the ionic state is conducive to absorption. The experiment shows (Chen et al. 2019) that the higher the bioavailability of heavy metals in the living environment of plants, the stronger the absorption capacity of plants for heavy metals. This is because pH can affect not only the availability of heavy metals in a plant's environment but also the plant. In extremely acidic soil conditions, plants cannot survive. That is, there is no enrichment ability. Qiu et al. (2008) conducted experiments on Ni enrichment of *A. corsicum* and *A. murale* in the cruciferous family. They showed that the Ni absorption capacity of the two plants increased by two to three times when the pH value increased from 4.97 to 6.08. It may be that the decrease of H+ in soil relatively improves the absorption of metal ions by plant root complexes, or it may be that the decrease in the mobility of metal ions in soil and the weakening of the competitive adsorption between ions increase the absorption of Ni by roots (Urszula et al. 2004).

Oil Content

The removal rate of soil pollutants is one of the key indexes to directly evaluate the effect of phytoremediation. The concentration of oil pollution is the key environmental factor limiting the phytoremediation effect, and it is also the main evaluation index to determine the phytoremediation effect of tested plants in response to the stress of different oil pollution concentrations (Jing et al. 2019b). Wang et al. (2023) studied the repair effects of *Rudbeckia hirta* L. on petroleum hydrocarbons with different oil content. They found that soil with oil pollution concentration $\leq 6\%$ significantly promoted the plant height, root length, underground dry weight, root vigor, and root the head ratio of *Rudbeckia hirta* L. but significantly inhibited *Rudbeckia Hirta* L. when the oil pollution concentration was $\geq 8\%$. This is because the increase in the concentration of crude oil pollutants will significantly increase the soil viscosity and hydrophobicity (Qi et al. 2015), hinder the respiration of plant roots, and destroy plant root tissues through osmosis (Li et al. 2020), reduce soil water content in the micro-domain environment, limit the effective circulation of soil nutrients, and thus change soil biological and non-biological environmental factors.

The effect of heavy metals on plant growth shows the phenomenon of low promotion and high inhibition. That is, low concentrations of heavy metals can promote plant growth, and the amount of heavy metals accumulated by plants increases with the increase of heavy metal concentration (Li et al. 2008). Through experiments, Tang et al. (2018) and Wei et al. (2014) found that at low concentrations, Cr had a promoting effect on the chlorophyll content and biomass of wetland plants Reflorum and bamboo willow. With the increase of heavy metal concentration, plants can make corresponding physiological adjustments to the stress to alleviate or eliminate the damage caused by heavy metal stress to plants and maintain the normal growth of plants. However, plants' ability to relieve heavy metal stress has a certain threshold value. Under high concentrations of heavy metal stress, plants' ability to enrich heavy metal will decrease with the increase of metal concentration. This is because high concentration of toxic heavy metals has a destructive effect on plant cell structure, resulting in plant wilt and even death.

When heavy metals coexist with petroleum hydrocarbons, the effect of plant enrichment is different from that in the presence of a single pollutant, resulting in antagonistic or synergistic effects. The mechanism of this process is very complex, involving many factors such as the type, concentration, plant species, and tissue location of heavy metals and petroleum hydrocarbons, so further studies are needed.

CONCLUSION

With the continuous optimization and deepening of phytoremediation technology, these research results have significantly reduced the difficulty of remediation of heavy metals in soil contaminated by petroleum hydrocarbons and, at the same time, reduced the treatment cost and the possibility of secondary pollution. At present, most studies focus on single or multiple phytoremediation of a few heavy metals, and the understanding of the co-removal effect of petroleum hydrocarbons and heavy metals is still very limited, but this effect is the best solution for bioremediation of contaminated sites, especially when the heavy metal pollutant load is high. The amount of heavy metals in oily sludge is large, and the concentration is large. In order to strengthen the repair effect of plants on heavy metals, the following aspects can be considered:

(1) Strengthen the interaction between plants and various organisms to achieve the purpose of enrichment of heavy metals.

(2) At present, the application and development range of intercropping, intercropping, and rotation restoration models of hyperaccumulator is relatively narrow, so it is possible to explore the growth cycle of hyperaccumulator and enrich metals many times or transfer heavy metals from hyperaccumulator with a large amount of heavy metals in their bodies so that the hyperaccumulator can make secondary utilization.

(3) Explore the use of genetic engineering to improve hyperaccumulators to improve the metal enrichment ability of plants.

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