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Research Progress of Soil Pollution and Its Remediation Technology

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Abstract:
As an important component of the Earth's ecosystem, soil health is directly related to ecological security and human health. In recent years, the combined pollution of heavy metals and microplastics has become increasingly serious, which seriously weakens the ecological function of soil and brings potential health risks. In this paper, typical pollution cases and technical literature are systematically reviewed, focusing on the mechanism of combined pollution of heavy metals and microplastics, to analyze the application efficiency and limitations of bioremediation (Microbial fuel cell, phytoextraction and plant-microbe synergy) and physicochemical remediation (thermal desorption, leaching, solidification-stabilization) technologies. Phytoremediation relies on hyperaccumulators (e.g., pteris vittata) that accumulate arsenic, but is limited by the growth cycle and multitargeting defects. Microbial fuel cells are highly efficient for the degradation of organic pollutants, but are not suitable for large-scale applications. As a carrier of pollutants, microplastics significantly amplify the risk of heavy metal migration, but the existing technology has not yet formed a systematic solution to their synergistic treatment. This study provides a theoretical basis for constructing a soil treatment path of"Pollution removal-ecological function restoration", and has important practical significance for improving the overall health and sustainable use of soil systems.

Keywords: Soil treatment, soil pollution, soil remediation technology

1. Introduction

Soil is the core carrier to maintain the function of terrestrial ecosystems, and its health status directly affects the safety of agricultural production, biodiversity protection and human living environment. With the acceleration of industrialization and the development of intensive agriculture, pollutants enter the soil system through atmospheric deposition and sewage irrigation, causing problems such as heavy metal accumulation, organic matter residue and microbial community imbalance, which can lead to the degradation of soil function and even the toxic transmission of ecological chain. How to ensure the sustainable use of land resources, scientifically repairing damaged soil and blocking the diffusion path of pollution has become a key issue in the field of environmental science.

Soil remediation refers to the remediation of contaminated soil by physical, chemical or biological means to remove or reduce the concentration of harmful substances and restore soil ecological functions and productivity, reducing the threat of pollutants to the environment and human health. Its core objectives include the removal or stabilization of pollutants, the restoration of ecological functions, and the sustainable use of land resources.

At present, the research of soil remediation is developing in the following six directions: The Bioremediation of green and environment-friendly, the comprehensive remediation of joint hybridization, the in-situ remediation, the remediation based on environmental functional materials, the rapid site remediation based on equipment, the decision support system of soil remediation and the post-remediation evaluation[1]. Among them, microbial remediation technology has become a hot topic. Chu Haiyan's team at the Nanjing Institute of Soil Sciences of the Chinese Academy of Sciences constructed a synthetic flora, and Liao Xiaoyong's team at the Institute of Geographical Resources of the Chinese Academy of Sciences developed a combined chemical oxidation-microbial technology, increasing Polycyclic aromatic hydrocarbon degradation efficiency by 10-20%. At the same time, phyto-bioremediation is also an important part of global soil remediation. The Southwest University team used anthocyanins to enhance the earthworm-ramie system, which increased the cadmium accumulation of ramie in cd-contaminated soil by 99%-107%, by regulating rhizosphere resistance genes (such as CZCA) for Synergy, Faisalabad Agricultural University developed biochar co-composting (COMBI) technology to reduce cadmium accumulation in sunflower grains by 94% and activate the antioxidant defense system.

This paper takes soil remediation as the core theme, analyzes the development status of soil remediation and discusses the future development trend of soil remediation technology by sorting out typical pollution cases and soil remediation technologies, it provides theoretical support for the construction of a soil management system of"-Source Prevention and control-precise remediation-intelligent management", and helps to achieve the synergistic goal of soil health and human sustainable development.

2. The status of soil pollution

The global soil pollution is characterized by complex, regional and hidden characteristics, and the types of pollution and pollution ways are diversified. At present, soil pollution mainly includes organic pollutants, heavy metals, radioactive elements and biological pollution, which pose a serious threat to soil quality and the ecosystem. Among them, heavy metal and microplastic pollution have become the core challenge of soil pollution prevention and control due to their extensive coexistence, synergistic toxicity amplification effect and technical governance bottleneck[2].

2.1 Heavy metal pollution

Because of its special ecological function and strong self-purification ability, soil has become the carrier and destination of heavy metal pollutants. The exogenous heavy metal pollutants in the atmosphere and water environment enter the soil by dry deposition, rainfall, surface runoff, sewage irrigation and other ways. When the content of heavy metals in soil exceeds a certain limit, it will lead to degradation of soil function, endanger the safety of crops, and cause serious harm to human health and the ecological environment. Heavy metals are considered to be one of the most serious environmental problems in the world because of their concealment, long-term, irreversibility and high toxicity.

Hg, Cd, Pb and As are the main heavy metals that cause soil pollution; it also includes common elements such as zinc (Zn) , copper (CU) and cobalt (CO) , which are toxic. Heavy metals can not be decomposed by microorganisms in soil, so they can accumulate in soil, affect soil properties, and even be transformed into more toxic alkyl compounds, which can be absorbed and enriched by plants and other organisms, and then through the food chain in the human body, the accumulation of direct impact on plants, animals and even human health. The survey data showed that cadmium (CD) had the highest frequency of heavy metal pollution in the soil, accounting for 25.2%, followed by nickel (Ni) and mercury (Hg) , with 5.17% and 3.31%, respectively. Arsenic (As) and lead (PB) pollution probabilities are relatively low, respectively, 0.92% and 0.72%. These data reflect differences in the mobility and source intensity of different elements in the environment[3].

The sources of soil heavy metal pollution include metal mining and smelting, chemical industry production, heavy metal pesticides, sewage irrigation and fertilizer application, and high geological background values, the main ways of heavy metal pollution are the sedimentation of waste gas, the irrigation of waste water, and the dissolution and diffusion of solid wastes such as Non-ferrous metal into the soil. The harm of heavy metal pollution is reflected in many aspects such as plants, animals, human

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health and so on. The heavy metals in soil will have a certain toxic effect on plants, causing a series of physiological characteristics such as plant height, main root length and leaf area to change. Huang Yuyuan carried out an in-depth analysis and research on the status of agricultural water use and the quality of vegetable products in Guangzhou City, and all kinds of vegetables will be polluted in different degrees [4]. At the same time, the enrichment of various heavy metal elements in the soil has brought a serious threat to the survival and reproduction of soil animals. Sun Xianbin studied the effects of heavy metal pollution on the community and diversity of soil animals in Huainan, the composition and quantity of soil animal community decreased with the aggravation of pollution [5]. Among the hazards of heavy metals, the most concerning is the harm to the human body. Different heavy metal elements threaten human health and safety in different ways. When excessive CD is ingested or inhaled, it can cause a series of lesions in various organs of the body, which can lead to bone effects characterized by decreased bone mineral density and increased fracture incidence. PB can lead to the decline of reproductive function and immunity in various organisms, including human beings. When the mass ratio of blood lead in the human body reaches 600 μg/g — 800 μg/g, it will appear as dizziness, headache and memory decline. Long-term consumption of Cr-containing foods, the human body will appear to varying degrees of skin and respiratory system lesions, as well as ulcers and inflammation. Long-term Ni inhalation can cause nasal and lung cancer, and can cause contact dermatitis, pneumonia and other diseases. When the metal HG enters the human body, it can combine with many negatively charged groups such as sulfhydryl groups in enzymes or proteins in the body, affecting energy production, protein and nucleic acid synthesis, thus affecting the cell normal function and the growth. According to Zeng Zhaohua's research, the occurrence and development of cancer is related to the mass fraction of SN in the soil and environment. People living in areas with high mass fraction of SN have higher cancer mortality. Obviously, the soil, the heavy metal pollution have the enormous harm to the human body[6].

2.2 Microplastic pollution

As a kind of small-sized plastic waste, the diameter of microplastics is generally less than 5 mm, and it is very difficult to be degraded in nature. Plastic is composed of a variety of synthetic or semi-synthetic organic polymer materials, including polyethylene (PE) , polypropylene (PP) , polystyrene (PS) , etc.

The main sources of microplastics in soil are agricultural films, Soil conditioner, irrigation water, plastic products and atmospheric deposition[4]. Agricultural film is a kind of plastic film widely used in agricultural production. The main materials of agricultural film are PE and PVC materials. PE film has light weight and good light transmittance, while PVC film has good thermal insulation and poor light transmittance. When burned, it produces toxic and harmful substances. Compost products and sludge are rich in plant nutrients and organic carbon and are therefore widely used as Soil conditioners to improve soil physical and chemical properties and increase soil nutrient content and crop yield. At present, most of the sludge treatment technology and composting technology are difficult to remove microplastics, so the agricultural use of sludge and compost products is also an important source of microplastics in farmland soil. Due to the characteristics of small particle size, large specific surface area and strong hydrophobicity, microplastics inevitably interact with other pollutants when exposed to the soil environment. Microplastics act as carriers for the transport and transformation of pollutants in the soil environment. At present, Persistent organic pollutants, heavy metals and antibiotics have been detected on the surface of microplastics. As a good carrier of these substances, microplastics have a certain compound effect on the soil environment and organisms, has attracted the attention of scholars. Relevant scholars have carried out research on the combined effects of microplastics and other pollutants. Studies have shown that the release of heavy metals and microplastics into the soil environment will occur after the geochemistry process, microplastics can adsorb heavy metals in soil, relevant scholars have also studied the interaction between microplastics and heavy metals. Hodson et al. found that the surface of microplastics in the soil environment is charged during wear and adsorbs metal cations, and the adsorption kinetics conforms to the nonlinear adsorption equation, moreover, microplastics as carriers have the potential to increase the adsorption of heavy metals in terrestrial environments [7].

3. Soil Remediation and rehabilitation programme

3.1 Bioremediation technology

Bioremediation is the use of the metabolic activity of an animal, a microorganism, or a plant, to reduce the content of heavy metals and other pollutants in the soil environment or by changing the chemical forms of heavy metals or organic pollutants in the soil to reduce their toxicity. Bioremediation technology has become a research hotspot due to its low carbon, economic and environmental friendliness. It mainly includes the following directions: Microbial fuel cell remediation (MFC) , phytoremediation technology and plant-microbe combined remediation.

3.1.1 Microbial fuel cells, MFCs

Microbial fuel cell is a technology that uses electricity-producing microorganisms to directly convert chemical energy into electrical energy. It does not consume external energy and has no secondary pollution during operation, which has attracted increasing attention. Research into biofuel cells began in 1911 when British botanist Potter, experimenting with yeast and E. coli, announced that microbes could be used to generate electricity. A Microbial fuel cell is a device that converts chemical energy into electrical energy using microbial catalysts [8]. In MFCS, most organic pollutants can be removed by oxidation near the anode, and the removal efficiency is high. This is because at the anode, the microbes can directly oxidize the organics, produce electrons and H + , and combine with electron acceptors such as O2 at the cathode to produce water, accelerating the decomposition of organic pollutants. The Microbial fuel cell works like this: the fuel is oxidized by Microbial metabolism in the anode chamber, the electrons travel through the external circuit to the cathode, and the protons travel through the proton exchange membrane to the cathode, the oxide is reduced in the cathode chamber under the action of a catalyst.

According to the mode of electron transfer, Microbial fuel cell can be further divided into direct Microbial fuel cell and indirect Microbial fuel cell[6].

MFCS was first used to treat chromium pollution in sewage, but its reduction effect on chromium in sewage is different. Wang et al. used MFCs technology to treat CR6 + contaminated wastewater in a batch mode, with synthetic CR6 + wastewater as cathode and anaerobic microorganisms as anode catalysts. At an initial pH of 2, the wastewater containing 100 mg · L-1 of chromium was completely removed within 150 h. This experiment confirms the possibility of simultaneous electricity generation and chromium reduction. The successful experience of remediation of chromium-containing wastewater by MFCS has inspired scholars to apply MFCs to the remediation of chromium-contaminated soil, and has proved its feasibility. Habibul et al. studied the effect of MFCs on the remediation of chromium-contaminated soil with different concentrations, and found that the highest removal rate could reach 99% , and the removal rate of chromium increased with the increase of the initial chromium concentration in the contaminated soil[9].

In general, most of the researches on MFCS start from the influencing factors of its system operation, and mainly focuses on how to improve the performance of MFCs and enhance its ability to repair soil and generate electricity. However, there are some problems in the remediation of contaminated soil by MFCS. The generated current is small, the soil conductivity is low, and the action range of current is limited. The remediation effect is more significant only in the area near the poles. At present, the remediation of contaminated soil by MFCS is mainly based on ex-situ remediation in the laboratory, which is insignificant in the face of a large area of contaminated soil in the world. Therefore, how to apply MFCs to the remediation of large-scale contaminated soil and expand its effective remediation area is worthy of further exploration.

3.1.2 Phytoremediation

Phytoremediation refers to the use of plants to extract, absorb, decompose, transform and immobilize toxic and harmful pollutants in soil, sediment, sludge, surface water and groundwater. The remediation process is controlled by many factors, such as plant species, soil physical and chemical properties, rhizosphere microorganisms and so on.

Phytoextraction refers to the use of hyperaccumulator plants to absorb heavy metals from contaminated soil and accumulate them in the aerial parts, and harvest the aerial parts of plants to remove pollutants. Plant extraction is divided into two categories, one is continuous phytoextraction, which directly selects hyperaccumulators to absorb and accumulate heavy metals in the soil; the other is induced phytoextraction, which involves the accumulation of heavy metals in the soil, in order to improve the efficiency of extracting heavy metals from soil, hyperaccumulators were planted and some substances which could activate heavy metals in soil were added. Hyperaccumulator refers to the ability of plants to take up and enrich high levels of heavy metals from soil or water, and to transport heavy metals from the underground part of the plant to the aboveground part in large quantities, relative to ordinary plants, showed a high enrichment factor. There are three definitions of hyperaccumulators: (1) the concentration of heavy metals in plant shoot reaches a critical value; (2) the bioaccumulation factor (the ratio of shoot heavy metal concentration to soil heavy metal concentration) is greater than 1; (3) transport coefficients (concentrations of heavy metals in the aerial part/underground part) > 1. The key of plant extraction technology is the screening of hyperaccumulators. More than 400 species of hyperaccumulators have been found in the world. In recent years, the research on plant extraction technology has become a research hotspot in the scientific community, and has also been promoted and applied in the engineering application of actual contaminated sites. Pteris vittata L. is

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the first hyperaccumulator of arsenic in the world. It has a strong ability to accumulate arsenic, and its ability to remove arsenic can be improved by cutting. In Chenzhou, Hunan province, Chen Tongbin and his colleagues have established the world's first demonstration site for phytoremediation of arsenic-contaminated soil. Pteris cretica L. and Pityrogramma calomelanos were also found to be arsenic hyperaccumulators in the genus Pteris. Zhang Xingfeng of the South China Botanical Garden of the Chinese Academy of Sciences has carried out research on the remediation potential of heavy metal-contaminated soils by forage grasses, hybrid Pennisetum num (L.) Leeke × P. purpureum Schumach and black seed Paspalum atratum cv. Reyan No. 11 were found to be excellent grass species for plant extraction technology, the former can remediate CD and Zn contaminated soil, and the latter can remediate CD contaminated soil. The results showed that EDTA and EDDS were efficient chelating agents for enhancing the extraction of heavy metals by plants. The addition of EDTA increased the ZN concentration in leaves, stems and roots of S. Nigrum by 231% , 93% and 81% , respectively Addition of EDDS resulted in 140% , 124% , and 104% higher Zn accumulation concentrations in leaves, stems, and roots of S. Nigrum, respectively.

Phytostabilization is the process of using plant roots to immobilize heavy metals in soil. Heavy metals are absorbed and accumulated by the root system, or adsorbed on the root surface, or fixed in the rhizosphere by root exudates. In addition, plant rhizosphere microorganisms (bacteria and actinomycetes) affect the chemical speciation of heavy metals in the rhizosphere by changing the rhizosphere soil properties (such as pH and EH) , which is also conducive to reducing the toxicity of heavy metals to plant roots. Plant immobilization can reduce the mobility and bioavailability of heavy metals in soil, and prevent the migration of heavy metals to groundwater and air and their transfer in the food chain. Plant immobilization technology does not remove heavy metals from soil in a real sense, but only fixes heavy metals in plant roots or rhizosphere soil, so it is necessary to carry out long-term monitoring of remediation soil. Plant immobilization has a broad application prospect in the remediation of tailings heaped land in arid and semi-arid areas, and can realize the vegetation reconstruction of such contaminated sites. Silphium perfoliatum Linn (Silphium perfoliatum) can be used to remediate Cd-contaminated soils.

Phytovolatilization is a method to remove Se, HG and As from soil by using some special substances or microorganisms secreted by plant roots. Plant volatiles technology is suitable for remediation of Se, Hg, and contaminated soils. Growing mustard in Se-contaminated soil can remove soil Se by volatilization form. Kenaf can make the soil in the trivalent selenium into volatile methyl selenium so as to achieve, to remove the purpose. Growing tobacco can convert mercury in the soil into gaseous mercury and remove mercury from the soil. The volatilization of gaseous Se, HG, As, etc. into the atmosphere is likely to cause secondary pollution, so it is necessary to properly dispose of plants and the harmful gases generated by volatilization.

Phytoremediation technology has both technical and economic advantages over traditional physical and chemical remediation technologies, which are mainly reflected in the following aspects: (1) it can simultaneously remediate contaminated soil and surrounding contaminated water; (2) low cost, and can be recovered by post-processing of heavy metals; (3) with environmental purification and beautification effect, high degree of social acceptability; (4) planting plants can improve soil organic matter content and soil fertility. However, phytoremediation technology also has disadvantages, such as the limited tolerance of plants to heavy metals and pollutants, phytoremediation is only suitable for medium-polluted soils. Soil heavy metal pollution is often a combination of several metals. A plant can generally only repair a heavy metal contaminated soil, and may activate other heavy metals in the soil. It grows slowly and takes a long time to remediate contaminated soil, so it is difficult to meet the requirements of rapid remediation of contaminated soil. At present, genetic engineering technology can overcome some of the weaknesses of the above phytoremediation technology, but the use of genetic engineering technology to cultivate genetically modified crops for the remediation of heavy metal contaminated soil is still at a relatively controversial stage, the genetically modified crops are prone to cause ecological safety problems such as species invasion and interbreeding.

3.1.3 Combined plant-microbe remediation

As an enhanced phytoremediation technology, phyto-microbial remediation of heavy metal contaminated soil has gradually become a research hotspot at home and abroad. This remediation method utilizes the coexistence of soil-microorganism-plant, gives full play to the respective advantages of plant and microbial remediation technology to make up for the shortcomings, and then improves the efficiency of phytoremediation of pollutants in soil. Finally, the aim of completely remediating heavy metal contaminated soil is achieved[10].

Mycorrhizal fungi in the rhizosphere play an important role in improving plant resistance to heavy metals and improving remediation efficiency. Mycorrhizal fungi can change the forms of heavy metals in the rhizosphere by secreting root exudates, thereby reducing the phytotoxicity and bioavailability of heavy metals. Inoculation with mycorrhizal fungi improves the extraction efficiency of As from soil by Pteris vittata. The mycorrhizal fungus Glomus Mosseae can change the cell wall composition of rice roots, reduce the uptake and accumulation of Cu in rice shoots, and enhance the resistance of rice to Cu. The results of pot and field experiments showed that inoculation with arbuscular fungi greatly enhanced the uptake and accumulation of Cu, Pb, and Zn in contaminated soil by bidens pilosa and Dracaena cochinchinensis. Teng Ying et al. also studied and established mycorrhizal fungi enhanced alfalfa rhizosphere remediation technology and nitrogen-fixing plant-rhizobium-mycorrhizal fungi Polycyclic aromatic hydrocarbon remediation technology of contaminated farmland soil. Different species of mycorrhizal fungi have different effects on the absorption of heavy metals by plants [11]. Some species are beneficial in improving the absorption of heavy metals by plants and thus improve the extraction efficiency of plants; however, some mycorrhizal fungi inhibit the absorption of heavy metals by plants and improve the resistance of plants to heavy metals. Therefore, mycorrhizal fungi should be selected reasonably according to different purposes. Mycorrhizal remediation (microbial remediation) is a kind of phytoremediation combined with microbial remediation. The key of mycorrhizal remediation is still phytoremediation; it is the development direction of microbial remediation to select excellent strains and apply them in phytoremediation.

3.2 Physical and chemical remediation technology

3.2.1 Thermal desorption method

Thermal desorption is an effective way to remediate contaminated soil by heating the contaminated soil to a critical point, where it evaporates and is treated collectively. This technology can be widely used in the in-situ or ex-situ remediation of high-concentration organic contaminated soil. For some low boiling point heavy metals (such As HG, Se and As) contaminated soil, it has now entered the field application stage. At present, the Environ Mental Protection Agency, the EPA recommended method for use in the higher mercury concentration range (> 260 mg/kg) , has a large number of successful cases in foreign countries.

Thermal desorption is one of the heat treatment methods, which makes the pollutants in the soil escape through the process of phase change, rectification, oxidation and pyrolysis by direct or indirect heating, the invention relates to a technical method which is further separated from the soil and removed. The method is commonly used for treating the pollution of substances such as polychlorinated biphenyls, pesticides, chlorine-containing solvents and hydrocarbons. The thermal desorption of nitrobenzene in soil was studied by Zhang Pan et al. . The results showed that the thermal desorption efficiency of nitrobenzene was 82.88% under the optimum conditions, this provides a basis for the remediation of nitrobenzene in contaminated sites by thermal desorption. Taking the most mature Ex situ thermal desorption as an example, the remediation process of contaminated soil can be divided into three stages: pretreatment, thermal desorption and post-treatment. First, the contaminated soil is fed into a heating device for continuous heating. When the soil reaches critical point temperatures, pollutants begin to evaporate. Finally, the volatile products are collected and centralized.

The thermal desorption method has the advantages of simple process and mature technology, and can remove mercury in contaminated soil more thoroughly[12], Therefore, it is recognized as one of the permanent solutions for soil remediation. It is particularly applicable to soils or wastes with high mercury content, and to scenarios where Mercury recycling is required. However, it should be pointed out that thermal desorption technology also has some problems to be solved urgently, such as high energy consumption and investment cost, expensive equipment and long desorption time.

3.2.2 Method of washing restoration

Soil washing remediation technology is a process in which water or an aqueous solution containing a washing aid, an acidalkali solution, a complexing agent or a Surfactant agent are injected into the contaminated soil or sediment to elute and clean the contaminants in the soil. The treated soil can be safely reused after the treated wastewater reaches the discharge standard. This ex-situ remediation technology has been used in many countries to remediate heavy metal contaminated or mixed contaminated media. Because the technology requires water, remediation sites require proximity to water sources and increase costs due to the need to treat wastewater. It is still an important research topic to develop efficient and specific surface solubilizers, improve remediation efficiency, reduce equipment and sewage treatment costs, and prevent secondary pollution.

3.2.3 Curing-stabilization

Solidification-stabilization technology is used to fix pollutants in contaminated media and make them in a long-term stable state. It is widely used in the rapid control and remediation of soil heavy metal pollution, it has significant advantages for simultaneous treatment of multi-heavy metal contaminated soil.

The cost of this treatment technology is relatively low, and

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it can greatly reduce the cost of site pollution treatment for contaminated soil in some non-sensitive areas. Commonly used solidification stabilizers include fly ash, lime, asphalt and Portland cement, among which cement is the most widely used. In the United States, most of the non-organic pollution Superfund projects use solidification-stabilization technology for treatment. This technology has also been used in the heavy metal-contaminated soil of some smelting enterprises in our country and the contaminated soil of chromium slag after cleaning.

Solidification-stabilization technology fixes heavy metals by reagents and reduces their mobility. This method is widely used in the remediation of industrial and mining land, accounting for 23% of the market technology in our country. Cement solidification-stabilization treatment of organic and inorganic contaminated soils has been reported in the world. At present, it is necessary to strengthen the research and development of solidification-stabilization technology of organic contaminated soil, the development of new sustainable stabilization materials, and the research of long-term safety monitoring and evaluation methods.

3.2.4 Oxidation-reduction technology

Chemical oxidation-reduction in soil is achieved by adding chemical oxidants (e.g. Fenton reagent, ozone, hydrogen peroxide, potassium permanganate, etc.) or reducing agents (e.g. SO2, FE0, gaseous H2S, etc.) to the soil, it can react with the pollutants to purify the soil Generally, chemical oxidation is suitable for the remediation of soil and groundwater contaminated by organic pollutants. The application of chemical reduction method in the remediation of organic pollutants sensitive to reduction is a hot spot in current research. For example, the strong dechlorination of nanoscale powdered zero-valent iron has been recognized and applied to the remediation of soil and groundwater However, there are still some problems in the application of zero-valent iron reductive dechlorination technology, such as the passivation of iron surface activity, the failure of polymerization caused by soil adsorption, etc. , therefore, it is necessary to develop new catalysts and surface activation techniques.

4. The future development trend of soil treatment

4.1 Joint repair

In the face of complex soil pollution, a single remediation technology is often difficult to achieve the desired remediation effect. Therefore, the concept of combined restoration technology has been gradually improved and widely used. Combined remediation technology is to combine two or more remediation methods, give full play to their respective advantages, and solve complex soil pollution problems in a more efficient and economical way.

For example, phyto-microbial remediation technology, in which plant roots provide microorganisms with necessary carbon sources and a suitable living environment, and microbial activities improve the rhizosphere environment, has been widely used, promote plant growth and uptake of heavy metals. This interaction can significantly improve the stability and repair efficiency of the system. Bioremediation technology with microorganism and plants as the core is gradually becoming the mainstream with its good environmental compatibility and high economy[13]. The Sheyang Saline-alkali land restoration project in Jiangsu province used a combination of subsurface drainage and biological agents to reduce soil salinity from 8‰ to less than 3‰ . The core principle is that the organic acid secreted by the microbial agent can neutralize soil alkalinity and form aggregate structure to improve soil permeability, so that the sodium ion replacement efficiency is increased by 40% . Similarly, the Huanghua Saline-alkali land project in Hebei province used a combination of green manure returning to the field and planting salt-tolerant plants (Tamarisk and Jerusalem artichoke) to simultaneously reduce salinity and increase carbon sinks, reducing carbon emissions by 70 kg per hectare, that's the equivalent of 15 trees. Future technological breakthroughs will focus on genetic engineering enhancement. For example, designing engineered strains that can degrade petroleum hydrocarbons efficiently, cultivating heavy metal hyperaccumulators that increase biomass by three times, and the construction of "Soil animals-microorganisms-plants" collaborative remediation food web system.

4.2 Intellectualization and digital technology enabling

The repair process is shifting from an experience-dependent to a data-driven paradigm. The intelligent leaching system of petroleum hydrocarbon contaminated soil applied by desen environment in the United Arab Emirates monitors more than 200 parameters in real time through internet of things sensors, combining the AI algorithm dynamically optimizes material metering (error ≤0.5%) and dewatering efficiency (slurry dewatering rate 285%) to maintain stable operation in a desert high temperature (45 °C-RRB- and high humidity (90%) environment. The breakthrough of quantum sensing technology makes the real-time detection limit of heavy metals reach 0.01 μg/kg, which provides a"Perspective eye" for accurate diagnosis. The digital twin platform realizes the virtual verification of the repair scheme, improves the simulation accuracy to 92% , and greatly reduces the cost of trial and error. Together, these technologies promote the formation of a closed loop of"Intelligent monitoring-simulation optimization-precision control", so that the repair changes from"One size fits all" to scene customization.

4.3 Accelerating innovation in materials and equipment

Nanomaterials have shown great potential in targeted remediation, such as the reduction of organochlorine pollutants by zero-valent iron nanoparticles and the photocatalytic degradation of Polycyclic aromatic hydrocarbon by titanium oxide[14]. However, the environmental behavior and long-term ecological risk of nanomaterials still need to be further studied. At the equipment level, modular, mobile repair system have become a hot spot, such as modular washing equipment can quickly build a processing chain; The in-situ thermal repair equipment can work stably in the temperature range OF-5 °C to 50 °C through the phase change material temperature control technology. Engineering applications of cutting-edge technologies such as cold plasma oxidation and Microbial fuel cell will also drive equipment upgrades, which are expected to reduce costs by 60 per cent (from 800 yuan per square metre to 320 yuan per square metre) by 2030.

5. Conclusion

In this study, the remediation cases and technical literature of typical contaminated sites around the world were systematically reviewed, focusing on the combined pollution mechanism of heavy metals and microplastics and the application efficiency of biological and physicochemical remediation technologies, it reveals the paradigm shift of soil governance from single pollutant removal to ecosystem function restoration. The study found that bioremediation technology has become an important path for sustainable development because of its environmental compatibility-MFCs can degrade organic pollutants efficiently but its applicability to large-scale sites is limited, phytoremediation by hyperaccumulating species (such as Pteris vittata) for in situ extraction of heavy metals faces the bottleneck of slow growth and insufficient multi-targeting, in the physical and chemical remediation, the removal rate of organic pollutants by thermal desorption technology is more than 80%, but the energy consumption cost is still high, and the leaching method has the risk of secondary pollution, the long-term ecological safety of solidification-stabilization technology also lacks a unified global assessment standard. More seriously, the adsorption-migration effect of microplastics as an emerging carrier on heavy metals and Persistent organic pollutants further aggravates the complexity of compound pollution treatment, the existing technology has not yet formed a systematic solution.

In the future, three major breakthrough directions are proposed: first, developing a cross-media collaborative governance model to quantify the migration flux of soil-groundwater-air pollutants, and constructing a multi-media linkage remediation technical framework; second, exploring climate resilience-oriented remediation design, developing extreme temperature/drought-tolerant engineered strains and hyperaccumulators, and establishing dynamic prediction tools for pollutant bioavailability under climate change; Promote the sharing of global remediation knowledge base, integrate the advantages of in-situ rapid remediation equipment in developed countries and low-cost biotechnology in developing countries, forming the technology transfer mechanism that adapts to regional pollution characteristics, such as acid infiltration in mining areas and microplastic diffusion in tropical farmland. These explorations will promote the transformation of soil treatment from passive removal to active ecological resilience construction, which will not only provide scientific and technological support for ensuring the safe production capacity of 19.4% of the global polluted cultivated land, but also provide scientific and technological support for the construction of ecological resilience, by restoring the function of soil carbon sink, we can help achieve the goal of"Zero Carbon Earth", and finally realize the civilization transition from soil health to planetary health.

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