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Bioremediation technologies and mechanisms for pentachlorophenol contaminated soil and sediment of water environment

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ABSTRACT

Pentachlorophenol (PCP) has been widely used as pesticide in schistosomiasis-epidemic area of the middle and lower reaches of Yangtze River in china in recent decades. Widespread use of PCP resulted in PCP environmental contamination in soil and sediment of water environment in the epidemic area, which posed a potential danger to the aquatic ecosystems and human health. Bioremediation that involves the capabilities of plants, microorganisms and soil animals for pollutants clean-up is the most promising, relatively efficient and cost-effective technology for PCP removal in soil and sediment. The present study reviewed the bioremediation technologies and their bioremediation mechanisms for PCP contaminated soil and sediment of water environment, which including phytoremediation, microbial remediation, plant-microbial remediation, vermiremediation and composting. Based on the review, some suggestions for further study on bioremediation of soil and sediment polluted by PCP are put forward.

Keywords: Pentachlorophenol; Bioremediation; Microbial degradation; Phytoremediation

1. Introduction

Since the 1930s, pentachlorophenol (PCP) and its sodium salt (Na-PCP) have been widely used as a preservative, insecticide and fungicide worldwide [1]. In china, PCP has been widely used for killing oncomelania, the only intermediate host of schistosome, in the rice paddies and aquaculture ponds of 11 provinces, municipalities and autonomous regions with an area of about 1.48 × 10^4 km^2 in the middle and lower reaches of Yangtze River where schistosomiasis is epidemic in recent decades [1,2]. PCP has been classified as persistent organic pollutants (POPs) by the Stockholm Convention and a group 2B carcinogen by International Agency for Research on Cancer (IARC), and listed as a priority pollutant or restricted by china due to the potential health risks [3,4].

The impact of PCP used in decades on the environment will continue to be last for a long period of time [2]. And with the re-emergence of schistosomiasis in the traditionally epidemic areas, the production and use of PCP for snail elimination and schistosomiasis control warranted once again [5]. In recently years, PCP and other molluscacides were mixed used by some schistosomiasis prevention and control departments for enhancing the molluscicidal effect [2,5].

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Wide use of PCP resulting in wide occurrence of PCP at relatively high concentrations in soil and aquatic environment of epidemic area at present [3]. Over 96% of PCP eventually import into the soil and sediment in water environment, and the soil and sediment are the primary container of PCP in environment [3]. In particular, the killing of the snails, the schistosoma japonicum intermediate host, often need to spray pesticide containing PCP to ponds, fish ponds, ditches, lake shore and the bottom land of rivers and lakes and other fluctuation zone of water level, so the soil and sediment of water environment has higher levels of PCP residue [3]. The previous research demonstrated that PCP content in the soil and sediment of Dongting Lake, Poyang Lake beach, Wuhan section of the Yangtze River, the Tangxun Lake ponds, Miao River in Songzi of Hubei province exceed the ecological risk concentration of PCP in sediments (20–25 ng/g) [6–8]. The PCP pollution of soil and water environment in the affected areas will pose a potential threat to aquatic ecosystems and people's health in the epidemic area of the Yangtze River .

A variety of remediation techniques, including the physical and chemical remediation strategies and biological techniques, have been developed for the clean-up of PCP in soils. Bioremediation, which is defined as a process that uses microorganisms, green plants and soil animals to remediate the polluted sites for regaining their original condition [9,10]. Bioremediation technology has a broad prospect in remediation application for POPs pollution with lower application cost, lighter ecological risk and smaller side-effect to human beings and the environment. In the present review, the bioremediation technologies , including phytoremediation technology, microbial remediation technology, plant-microbial remediation technology, vermiremediation technology and composting technology, and the mechanisms involved in those technologies were summarized and prospected for PCP contaminated soil and sediment, with the aim to provide the certain reference foundation to promote the in-depth research of bioremediation technologies for PCP contaminated soil and ecological remediation application for polluted soil and sediment of water environment in the schistosomiasis-epidemic area in the middle and lower reaches of Yangtze River.

2. Classification of bioremediation technologies

In 1989, the bioremediation technology was applied in the United States as a useful cleanup technology for successfully dealing with the Exxon Valdez oil spill in Prince William Sound, Alaska for the first time on large-scale scale, which marked that the research of bioremediation technology start to be the hot spot and frontier in the field of environmental science [9]. Compared with conventionally physical and chemical remediation technologies, bioremediation has the uniquely significant advantages: (i) Easy to operate and maintain, thus the remediation cost is significantly reduced. (ii) In-situ implement at the contaminated site and with less environmental disturbance; (iii) Environmental friendly and are not easy to cause secondary pollution for remediation site. (iv) Suitable for large-scale and long-term remediation application [10,11].

Bioremediation technology has become a hot spot technology in the field of environmental remediation in the past ten years [10]. Bioremediation technologies for PCP contaminated soil and sediment can be classified as phytoremediation technology, microbial remediation technology, plant-microorganism combined bioremediation technology, vermiremediation technology and composting technology etc. [12–15].

3. Bioremediation technologies and mechanisms

3.1. Phytoremediation

Phytoremediation is a promising and hot remediation technology that uses plants to absorb and degrade contaminants from various polluted environment media [16]. This emerging technology with only solar powered, originally applied to decontamination of metals-contaminated soils, has been extended to organic contaminants thanks to the ecological and economic sustainability, high public acceptance, enhanced environmental safety, cost-effectiveness and in-situ remediation [3,17]. The soil or sediment could be ecologically remediated by phytoremediation technology through the way of plant metabolism, phytodegradation, phytostabilization, and rhizosphere microorganism degradation [18]. The contribution of plant uptake and accumulation to the dissipation enhancement of PCP was negligible. Accumulation of PCP in plant biomass only made a small contribution (less than 1%) to the total removal of toxicant [3]. Microbial degradation in the plant rhizosphere is the main mechanism involved in the phytoremediation of PCP contaminated soil and sediment. Plant rhizosphere is the soil nearest to the plant root system where roots release large quantity of secretions, metabolites and extracellular enzymes from living root hairs or fibrous root systems, which can increase the number and the activities of rhizosphere microorganisms, expand the activities sphere of rhizosphere microflora, improve the physical and chemical properties of rhizosphere and improve soil enzyme activity, thus promote the PCP removal in the plant rhizosphere [19,20].

The currently reported plant species that can be used for phytoremediation of PCP contaminated soil and sediment includes some woody plants, aquatic plants and crops. To date, various plant species including ryegrass (*Lolium perenne L*), radish (*Raphanus sativus*), willow (*Salix sp.*), poplar (*Populus sp*) and sunflower (*Helianthus annuus*) have been found to be promising candidates for phytoremediation of PCP [3,12,16,21,22]. Woody plants have the characteristics of rapid growth, large biomass and developed root system, and polluted environment remediation by woody plants has become a hot topic in the field of phytoremediation. In order to screen alternative plant materials for the phytoremediation PCP-contaminated soil, Yao et al. evaluated the growth adaptability of eight different tested poplars in PCP-contaminated soils, three varieties among them were more suitable for growing in the PCP polluted soil of 10–100 mg/kg and can be used as an alternative remediation plant for PCP contaminated soil [23]. Mills et al. reported that willow (*Salix sp.,'Tangoio'*) and poplar (*Populus sp. 'Kawa'*) growing in an open-ended plastic greenhouse could tolerate soil PCP concentrations of 250 mg kg, The degradation rate of PCP in soils planted soil was significantly higher than that of the un-planted group. Both trees stimulated a significant increase in soil microbial activity, thereby promoting the degradation of PCP in the soil [22].

The previously reported phytoremediation research for PCP contaminated soil mainly focused on crops. He et al. showed that rye grass could be used for the remediation of PCP contaminated soil, and rhizosphere degradation played an important role in the remediation process [24]. The degradation rate of PCP gradually decreased with the increase of the distance with the root surface. The degradation gradient followed the order: near rhizosphere > root compartment > far-rhizosphere soil zones where rye grass was grown, the PCP degradation gradients observed in the rhizobox of planted treatment appeared to be highest (98%) at 3 mm. The degradation rate of PCP (94%) in the rhizosphere region of rice was higher than that in the junction area of aerobic and anaerobic. He et al. studied PCP degradation ability of ryegrass and reported that within 90 days experiment as much as 85% and 83% of the added PCP (20 and 50 mg kg^{-1}) was depleted in the soil planted with rye grass at the two different PCP rates [25]. Meanwhile, the dissipation of PCP in spiked soils could be enhanced by phytoremediation with combined plants cultivation. Four plant species, White clover (*Trifolium repens*), ryegrass *(L. perenne)*, alfalfa *(M. sativa)*, and rapeseed *(B. napus)* were grown in combination to remediate PCP contaminated soil. Approximately 89.84% and 72.01% of PCP was dissipated by mixed planting of rapeseed and alfalfa, rape and white clover, respectively, which indicated that the effects of mixed plant cultivation would be proportionally cumulative, with the positive benefits of each individual plant species summing to a greater whole [26]. However, the remediation plants used for phytoremediaiton are mainly crops or forage plants and could be easily eaten by people and animals, which is may not conducive to the popularization and application of the scientific achievements.

The water environment conditions were not suitable for the growth of terrestrial plants when used in phytoremediation, and aquatic plants are more preferable for the remediation of PCP contaminated sediment in water environment. Zhao et al. utilized three species of aquatic macrophytes (*P. communis Trin, T. orientalis* and *S. validus Vahl*) to remediate pentachlorophenol (PCP)-contaminated sediments, more than 90% of the PCP was significantly removed by the planting after 90 d, bioaccumulation by three macrophytes was obvious [6]. The emergent wetland plant species, *Phragmites australis*, was investigated to evaluate the phytoremediation potential for cadmium and PCP co-contaminated soil under glasshouse conditions for 70 d, and removal rate of PCP increased significantly (70%) in planted soil by promoting the rhizosphere microorganisms and enzyme activity, thereby improving biodegradation of PCP [27]. Thus, it is feasible to apply aquatic plants to remediate the sediments contaminated by PCP.

When choosing the plants used for the phytoremediaiton, different plant species (terrestrial plant or aquatic plant) should be selected based on the targeted environmental conditions, such as the polluted soil or sediment in the epidemic area. Aquatic plants can be used as remediation candidates for water ponds, fishponds, canals and ditches contaminated with PCP. Woody plants such as poplar and willow can be chosen as the phytoremediation plants for contaminated soil in lake shore and river bottom land, and the crop or pasture plants can also be chosen as well. Finally, it is quite important for proper treatment of plant biomass after remediation completion.

3.2. Microbial remediation

Microbial remediation technology refers to the use of the functional microflora naturally occurring or cultured for cleaning up the toxic pollutants or degradation of targeted pollutants into non-toxic substances by promoting or enhancing the metabolic degradation function of microorganisms under suitable environmental conditions [14]. The microorganisms has the characteristics of abundant resources in the environment, the vigorous reproduction, easy to cultivation, adaptable to the environment [28], thus PCP can be thoroughly degraded and even completely mineralized without causing secondary pollution. Microbial remediation technology has become the main technology for bioremediation of PCP contaminated soil or sediment [29].

There are two types of remediation mechanisms involved in the microbial remediation of PCP polluted soil or sediments. First, PCP can be decomposed by the specific microorganisms that can utilize PCP as the sole carbon source and energy source [30]. The second mechanism refers to the pathway of co-metabolism that is PCP cannot act as the only carbon source and energy for microorganism in the environment. The degradation could occur when other compounds added as the carbon and energy sources [21]. For example, *Sphingobacterium multivorum* was able to degrade PCP through co-metabolism pathway, increasing degradation rate of PCP was observed when glucose was added as growth substrate, and there was no inhibition of substrate competition between glucose and PCP, degradation enzymes for PCP were induced by PCP itself [21].

To date, a variety of microorganisms including bacteria and fungi have been found to be able to degrade PCP. The species of bacteria include *Arthrobacter, Desulfridium, Mycobacterium, Pseudomonas, Rhodococcus, Serratia* and *chlorophenol Sphingomonas* [14,31–34]. The fungi used in PCP degradation include *Lentinula edodes*, mushrooms, *Phanerochaete, Rhizoctonia* and *Rhizopus* [35–38]. The above PCP degrading bacteria can obtain the PCP degradation efficiency of 40%–98% in different environmental media (such as soil, sludge, culture solution and degradation reactor) under certain conditions. Among the degrading microorganisms, Pseudomonas and white rot fungi are the most common bacteria and fungi that can degrade PCP [22]. Microbial degradation of PCP is divided into aerobic and anaerobic degradation [39]. In the process of microbial degradation, PCP is degraded or mineralized into low-chlorinated compounds through the way of oxidative dechlorination and reductive dechlorination by microorganisms [23].

At present, the efficiency of in-situ remediation of PCP-contaminated soil or sediment under nature environment by microbial remediation remains to be further studied. Due to the poor biodegradability of PCP, the bioremediation effect is unsatisfactory when bacteria and fungi applied solely for degradation, especially in the conditions of field application, because microorganisms often require more stringent growth conditions [1]. Plants can provide reasonable space for the growth of microorganisms. Therefore, plants can be used in combination with highly degradable microorganisms for enhancing the degradation efficiency of PCP. It is also possible to exploit modern molecular biology techniques for developing highly effective degrading microorganism to improve the ability and range of microbial adaptation, and thus to effectively apply microbial remediation technology in practice.

3.3. Plant-microbial remediation

The combination of plant and certain degradation microorganisms can significantly improve the remediation efficiency of PCP contaminated soil, because this technology possess an apparent advantage of lower energy consumption, low cost, wide application area, and high efficiency, and can give full play to the advantages of plant and microorganism [15,40]. The synergy generated between the plant and specific bacteria, fungi or rhizosphere microbes can promote the absorption and degradation of PCP [41]. Thus, fast remediation of polluted soil can be accomplished by choosing appropriate plants and microorganisms of high performance for achieving synergies. Takashi Nakamura (2004) using Chinese chives and genetically modified bacteria Pseudomonas gladioli M-2196 for co-remediation of PCP contaminated soil, the degradation efficiency of PCP in mixed system of plants and fungi (40%) was much higher than that of control group, and both collaborative degradation efficiency is higher than that of Chinese chives alone (30%) [16] .The degradation of PCP in the mycorrhiza was significantly higher than that in the rhizosphere. The removal rate of PCP was 73.6% for rye grass in 2 months in treatment of the PCP concentration of 20 mg/kg, and the degradation rate of PCP in the inoculated mycorrhizal fungus was 85.8%, 12.2% higher than that of non-inoculation. The effect of mycorrhizal fungi on PCP degradation can inhibit the accumulation of PCP absorption in the root of rye grass [42]. Chlorophenol *sphingosa ATCC39723* could reduce the toxic effect of PCP on plants, and it can obtain faster degradation rate and higher degradation efficiency of PCP [43].

The main mechanism of Plant-microbial remediation is that plant roots can provide carbon sources, nitrogen sources and necessary living places for the growth of microorganisms [10]. Root exudates can improve the degradation activity of microorganisms to pollutants. The vigorous growth of microorganisms enhances the degradation rate of pollutants and makes plants more superior space for growth. The plant-microbial combination system promotes the rapid degradation and transformation of pollutants. Therefore, the selection of optimal plant plays an important role in phytoremediation of POPs contaminated soil by plant-microbes interaction. The ideal plant should have some important characteristics, for example: (1) Larger biomass that is more resistant to contaminants and can tolerant high concentrations of contaminants; (2) Strong fibrous root system that provides the greatest possible root surface area for microbial activity; and (3) Deeper root systems that can penetrate deeper layers of soil [44].

3.4. Vermiremediation

Vermiremediation is a new bioremediation approach that uses the soil animals, mainly earthworms, for accelerated elimination and removal of various pollutants from soils by its biological way of decomposition, digestion and enrichment under artificial control or natural conditions [45–47]. At present, several research have been demonstrated that earthworms could enhance the bioavailability of PCP in soil through its biophysical and chemical behavior, thus improving the soil structure, enhancing the air and water diffusion capacity of soil, promoting the soil organic matter circulation and increasing soil microbial activity, thereby strengthen the bioavailability of PCP [48].

Earthworm is an important invertebrate in the soil, with strong environmental adaptability and reproductive capacity, showing much higher tolerance, bioaccumulation and resistance to pollution stress [48]. Lin et al. observed that earthworm s could enhance PCP removal from soil due to stimulation of indigenous PCP bacterial degraders [47].The earthworm species have certain impact on the soil microbial degradation of PCP, and could introduced new functional bacteria into soils for PCP biodegradation [49]. Earthworm (Eisenia foetida) has strong bioaccumulation potential for PCP in soil, with a bioaccumulation factor of 0.5 for PCP [50]. The introduction of earthworms during composting could promote the degradation of PCP. Li et al. (2011) investigated effects of two ecological earthworm species (*Eisenia foetida* and *Amynthas robustus E.Perrie*) and compost-immobilized mode on soil pentachlorophenol (PCP) degradation by laccase. The results showed that earthworms showed no significant influences on compost immobilized laccase activity, but could improve quantity and activity of soil microorganisms, and accelerate the soil PCP degradation. *Amynthas robustus E. Perrie* had higher enhancement effect on quantity and activity of soil microorganisms than *Eisenia foetida* [51]. Lin et al. study investigated the roles and mechanisms of earthworm (*Eisenia foetida*) on soil PCP degradation with sterile and non-sterile soil-compost treatment. Limited soil PCP degradation was observed in the control and sterile compost treatments, whereas the synergetic effects of earthworm and compost contributed to the PCP biodegradation acceleration by significantly improving microbial biomass and activities. The degradation microorganisms including indigenous bacterial families *Pseudomonadaceae, Sphingobacteriaceae* and *Xanthomonadaceae*, and fungal family Trichocomaceae, were stimulated by vermicomposting [47,52].

At present, there are few reports on vermiremediation of PCP contaminated soil, and the theory and technology of this aspect need to be further studied. For this technology, The soil animals earthworms need rather well defined conditions to survive and the costs might be too high to remediate large contaminated areas [47]. Vermiremediation can be used as auxiliary means of phytoremediation and microbial remediation to promote the removal of PCP in soil. If soil contains a high concentration of PCP residues and beyond the half-lethal concentration of soil animal, it is more appropriate for vermiremediation to be applied when PCP concentration in soil can be reduced through techniques such as phytoremediation and microbial remediation. More knowledge and research is required in the field so that the practical application of vermiremediation can be demonstrated on large scale.

3.5. Composting

Composting is traditionally intended to reduce volume and water content of vegetable wastes, to destroy pathogens and to remove odor-producing compounds. This technology is now utilized for bioremediation of soil or sediment contaminated by organic pollutants including PCP using the active microorganisms (bacteria, fungus, etc.) [13,53]. For example, over 90% of the chlorophenols were removed during 6 months of composting period in a pilot-scale composting experiment by two different inoculants (straw compost and remediated soil) [54]. And an average of 60% mineralization of [14C] PCP was obtained in 4 weeks in 1-kg piles with or without inocula in a bench-scale experiment [55]. A bench-scale composting system was constructed for successful bioremediation of PCP contaminated soil by microbial activity in the material, and 80% of PCP was removed in a 6 week period. Losses of PCP were due primarily to biotic processes [47]. Composting can be controlled by the compost environment conditions, promote the breeding of microorganism and metabolic activity, degradation and transformation of organic matter to produce a large amount of heat, make the heap temperature rise rapidly, increased the microbial metabolic rate, so as to improve the treatment effect of hazardous waste.

White rot fungi are commonly used microorganisms in the composting of POPs contaminated soil and sediment. Jiang et al. (2006) investigated the feasibility of employing composting technology by inoculating free and immobilized white rot fungi, *Phanerochaete chrysosporium* for the bioremediation of the contaminated soils, The degradation rate of PCP in compost with inocula was higher than that without inoculation and after 60 d composting, over 94% PCP in the compost was degraded, the effect by immobilized fungi was better than that by nonimmobilized one [53]. Therefore, the method of composting with immobilized *P. chrysosporium* is effective for the bioremediation of PCP-contaminated soil. The above studies showed that adding degradation microorganisms during composting can improve the degradation efficiency of PCP in composting and obtain higher degradation efficiency by immobilizing the degrading microorganisms than using inoculation of free bacteria alone [53].

To improve the bioremediation efficiency of composting for PCP contaminated soil, a certain amount of organic matter could be added to the pile body for promoting the growth of indigenous microorganisms. Addition of nutrients to the compost pile increases the metabolic activity of indigenous microbes, resulting in a faster rate of PCP degradation in the early stages of compost [54]. Temperature is crucial for composting degradation of PCP, with PCP degrading at 2% day^{-1} in the composting lab and 0.3%–1.3% day^{-1} in the field as the temperature in the laboratory is maintained at around 20°C, the field is difficult to maintain at this level and therefore has a negative effect on the degradation of PCP [54]. After some time of composting, the microbial activity in the pile increases. At this time, the degradation of PCP can be promoted by appropriately adding substrates and supplementing the carbon source and energy required by microorganisms. For example, Laine found that after two months of compost treatment with different inoculants, there was no significant difference in the degradation rates of PCP among the groups, reaching more than 80%, but the degradation rate of PCP exceeded 90% by adding higher soil PCP to each pile [56]. Composting of PCP-contaminated soils with a 50-m^3 body made of conditioning agents, organic matter and contaminated soils was investigated. The PCP concentration was reduced from 212 mg/kg in the first summer to 30 mg/kg, PCP decreased by 85.85%. The PCP content in the pile was further reduced to 15 mg/kg in the second summer. The number of PCP-degrading bacteria in the reactor reached 5×10^6 cfu/g. This study shows that the reduction of PCP is mainly due to the compost promoting the growth of microorganisms in the reactor resulting in PCP degradation [57]. This indicated that composting technology could promote the amount of microorganisms in the soil and enhance the microbial activity to promote the degradation of PCP in the soil. In the later stage of composting, the vitality of microbes could be increased in the pile body by adding nutrients and energy needed for the growth of microorganisms, which improving the PCP degradation efficiency or even completely mineralize PCP in the process of composting.

During composting process, the pollutants can disappear via different mechanisms such as mineralization by microbial activity, transformation to products, volatilization and formation of none tractable bound residues with organic matter etc [58]. Compared with other bioremediation technologies, composting technology has relatively lower operating and operating costs, simple operation and design, and relatively high processing efficiency. Combined with the realization of harmless, reduction and resource-based solid waste, composting technology provides a new idea for the harmless treatment of PCP contaminated dredged sediments of river and lake.

4. Problems and prospects

There is a high level of PCP in soil and sediment in the schistosomiasis epidemic area in the middle and lower reaches of the Yangtze River. It is necessary to solve the PCP pollution in the water environment by using bioremediation technology that is cost-effective, green, low ecological risk, simple in operation and maintenance, and can be applied in-situ and has a broad application prospects. At present, certain progress has been made on the theory and practice of PCP bioremediation in soil and sediment, but there are still many aspects of in-depth research in bioremediation filed need to be carried out.

For example, in the research process of PCP biodegradation, isotope-tracing technique can be used to track the transformation process of PCP in sediments and organisms (plants, microorganisms and animals) for revealing the degradation pathway of PCP in environmental media and organisms more accurately. For the mechanism of bioremediation, the study on the relationship between rhizosphere microorganisms, the composition and content of root exudates and the PCP remediation efficiency, the research on the isolation and identification of metabolites of PCP in vivo and the ecotoxicity of degradation products have to be further studied. In the field of plant-microbial combination remediation, plants and microorganisms with the higher degradative capabilities for PCP should be screened continuously by improving the genetic characteristics through molecular biology, to improve the plant growth rate or biomass and remediation efficiency. The genetic properties of microorganisms could be improved by molecular biology techniques such as genetic engineering to improve microbial remediation. At present, there is little research on the bioremediation technology for PCP using soil animals and the remediation mechanism is not thorough enough. The theory and technology in this respect need to be further studied. The combination of soil animal remediation technology, microbial remediation technology and phytoremediation can maximize performance of the advantages of technology. In the compost treatment of PCP-contaminated sediments, functional microorganisms and companion bacteria can be purposefully combined according to the synergistic relationship of microorganisms to construct a microorganism combination with high decomposition efficiency and stable effect, and its adaptability and function in compost environment in-depth study.

For engineering application of phytoremediation to remediate PCP contaminated sediment, applicable plants should be screened with characteristics of strong depuration effect, high pollutants resistance and strong ability to survive in water logging conditions, which is appropriate for ecological remediation projects for lake, river water, such as constructed wetlands, ecological floating island and ecological bank slope, etc. Meanwhile, further research should be conducted including the effect of mixed planting of aquatic plants on the phytoremediation efficiency of PCP contaminated sediments, the application of aquatic plants combined with highly effective microorganisms for ecological remediation of PCP contaminated sediments in large scale and the interaction of various surfactants on the phytoremediation.

In short, there is increasing attention for bioremediation due to its cost-effective, convenient operation and green characteristics. It is believed that the bioremediation theory for POPs is certain to be enriched and achieved as more bioremediation technologies are developed for PCP contaminated soil and sediments.

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References

[1] N. Hechmi, L. Bosso, L. El-Bassi, R. Scelza, A. Testa, N. Jedidi, M. Rao, Depletion of pentachlorophenol in soil microcosms with Byssochlamys nivea and Scopulariopsis brumptii as detoxification agents, Chemosphere, 165 (2016) 547–554.

[2] W. Zheng, H. Yu, X. Wang, W. Qu, Systematic review of pentachlorophenol occurrence in the environment and in humans in China: not a negligible health risk due to the re-emergence of schistosomiasis, Environ. Int., 42(1) (2012) 105–116.

[3] L. Zhao, C. Zhu, C. Gao, J. Jiang, J. Yang, S. Shao, Phytoremediation of pentachlorophenol-contaminated sediments by aquatic macrophytes, Environ. Earth. Sci., 64 (2011) 581–587.

[4] J. Ge, J. Pan, Z. Fei, J. Wu, J. Giesy, Concentrations of pentachlorophenol (PCP) in fish and shrimp in Jiangsu Province, China, Chemosphere, 69 (2011) 164–169.

[5] Z.Y. Wu, G.F. Zhao, H.D. Zhou, K.L. Li, M. Zeng, K. Li, P.W. Zhang, H. Hao, Pollution characteristics and potential risks of phenolic compounds in schistosomiasis epidemic areas, Environ. Sci., 33 (2012) 1682–1686.

[6] B. Yao, L.L. Zhou, X.W. Wei, F. Liu, H. Shang, G.U. Xue, Investigation on microbes characteristics of soil contaminated by pcp in flood land of typical snail fever region-a case study on Miao-he, J. Agro-Environ. Sci., 29 (2010) 1509–1514.

[7] B. Zhang, M.H. Zheng, P.Y. Liu, Z.C. Bao, Distribution of pentachlorophenol in Dongting Lake environmental medium, China Environ. Sci., 21 (2001) 165–167.

[8] Z.W. Tang, Z.F. Yang, Z.Y. Shen, J.F. Niu, Pentachlorophenol residues in suspended particulate matter and sediments from the yangtze river catchment of wuhan, china, B. Environ. Contam. Tox., 78 (2007) 158–162.

[9] P.H. Pritchard, J.G. Mueller, J.C. Rogers, F.V. Kremer, J.A. Glaser, Oil spill bioremediation: experiences, lessons and results from the exxon valdez oil spill in Alaska, Biodegradation, 3 (1992) 315–335.

[10] C. Niti, S. Sunita, K. Kamlesh, K. Rakesh, Bioremediation: An emerging technology for remediation of pesticides, Res. J. Chem. Environ., 17 (2013) 88–105.

[11] L.W. Perelo, Review: In situ and bioremediation of organic pollutants in aquatic sediments, J. Hazard. Mater., 177 (2010) 81–89.

[12] E.K. Miller, W.E. Dyer, Phytoremediation of pentachlorophenol in the crested wheat grass (Agropyron cristatum Ã-desertorum) rhizosphere, Int. J. Phytoremediat., 4 (2002) 223–238.

[13] G. Zeng, Z. Yu, Y. Chen, J. Zhang, H. Li, M. Yu, M. Zhao, Response of compost maturity and microbial community composition to pentachlorophenol (PCP)-contaminated soil during composting, Biores. Technol., 102 (2011) 5905–5911.

[14] K.A. Mcallister, H. Lee, J.T. Trevors, Microbial degradation of pentachlorophenol, Biodegradation, 7 (1996) 1–40.

[15] Y. Han, M. Li, Phyto-microremediation technology on treatment of eutrophic water, Technol. Water. Treat., 38 (2012) 1–11.

[16] T. Nakamura, T. Motoyama, Y. Suzuki, I. Yamaguchi, Biotransformation of pentachlorophenol by Chinese chive and a recombinant derivative of its rhizosphere-competent microorganism, Pseudomonas gladioli M-2196, Soil. Biol. Biochem., 36 (2004) 787–795.

[17] S. Roy, S. Labelle, P. Mehta, A. Mihoc, N. Fortin, C. Masson, R. Leblanc, G. Châteauneuf, C. Sura, C. Gallipeau, Phytoremediation of heavy metal and PAH-contaminated brown field sites, Plant. Soil, 272 (2005) 277–290.

[18] B.R. Glick, Phytoremediation: synergistic use of plants and bacteria to clean up the environment, Biotechnol. Adv., 21 (2003) 383–393.

[19] C. Urrutia, O. Rubilar, C. Parede, E. Benítez, R. Azcón, M.C. Diez, Removal of pentachlorophenol in a rhizotron system with rye grass (Lolium multiflorum), J. Soil. Sci. Plant. Nut., 13 (2013) 499–510.

[20] A. Singh, Phytoremediation strategies for remediation of uranium-contaminated environments: a review, Crit. Rev. Env. Sci. Tec., 42 (2012) 2575–2647.

[21] T. Mills, B. Arnold, S. Sivakumaran, G. Northcott, I. Vogeler, B. Robinson, C. Norling, D. Leoni, Phytoremediation potential of maize (Zea mays L.) in co-contaminated soils with pentachlorophenol and cadmium, Int. J. Phytoremediat., 15 (2013) 703–713.

[22] T. Mills, B. Arnold, S. Sivakumaran, G. Northcott, I. Vogeler, B. Robinson, C. Norling, D. Leonil, Phytoremediation and long-term site management of soil contaminated with pentachlorophenol (PCP) and heavy metals, J. Environ. Manage., 79 (2006) 232–241.

[23] B. Yao, Y.Z. Xiang, H. Shang, F. Liu, X.N. Liu, W.J. Ren, Screening of candidate plants for phytoremediation of pentachlorophenol-contaminated soil, J. Mt. Agric. Biol., 28 (2009) 104–108.

[24] Y. He, J. Xu, C. Tang, Y. Wu, Facilitation of pentachlorophenol degradation in the rhizosphere of rye grass (Lolium perenne L.), Soil. Biol. Biochem., 37 (2005) 2017–2024.

[25] H. Zhang, Z. Dang, L.C. Zheng, X.Y. Yi, Remediation of soil co-contaminated with pyrene and cadmium by growing maize (Zea mays L.), Int. J. Environ. Sci. Technol., 6 (2009) 249–258.
[26] N. Hechmi, N.B. Aissa, H. Abdenaceur, N. Jedidi, Phytoremediation efficiency of a pcp-contaminated soil using four plant species as mono- and mixed cultures, Int. J. Phytoremediat., 16 (2014) 1241–1256.
[27] N. Hechmi, N.B. Aissa, Uptake and bioaccumulation of pentachlorophenol by emergent wetland plant phragmites australis (Common Reed) in cadmium co-contaminated soil, Int. J. Phytoremediat., 17 (2015) 109–116.
[28] K. Vaidehi, S.D. Kulkarni, Microbial remediation of polycyclic aromatic hydrocarbons: An overview, Res. J. Chem. Environ., 16 (2012) 200–212.
[29] B. Singh, J. Kaur, K. Singh, Microbial remediation of explosive waste, Crit. Rev. Microbiol., 38 (2012) 152–167.
[30] W. Wang, S. Wang, J. Zhang, Z. Hu, X. Zhang, J.M. Sierra. Degradation kinetics of pentachlorophenol and changes in anaerobic microbial community with different dosing modes of co-substrate and zero-valent iron, Int. Biodeter. Biodegr., 113 (2016) 126–133.
[31] S. Shail, R. Chandra, D.K. Patel, R. Vibhuti, Isolation and characterization of novel Serratia marcescens (AY927692) for pentachlorophenol degradation from pulp and paper mill waste, World. J. Microb. Biot., 23 (2007) 1747–1754.
[32] C.F. Yang, C.M. Lee, C.C. Wang, Isolation and physiological characterization of the pentachlorophenol degrading bacterium sphingomonas chlorophenolica, Chemosphere, 62 (2006) 709–714.
[33] P.M. Radehaus, S.K. Schmidt, Characterization of a novel pseudomonas sp. that mineralizes high concentrations of pentachlorophenol, Appl. Environ. Microb., 58 (1992) 2879–2885.
[34] B. Tartakovsky, M.J. Levesque, R. Dumortier, R. Beaudet, S.R. Guiot, Biodegradation of pentachlorophenol in a continuous anaerobic reactor augmented with desulfitobacterium frappieri PCP-1, Appl. Environ. Microb., 65 (1999) 4357–4362.
[35] Y. Huang, A.O. Xiao, The mechanisms of PCP biodegradation and the capacity for PCP degradated by ECMF, Ecol. Environ., 15 (2006) 1080–1085.
[36] B.C. Okeke, A. Paterson, J.E. Smith, I.A. Watsoncraik, Comparative biotransformation of pentachlorophenol in soils by solid substrate cultures of lentinula edodes, Appl. Microbiol. Biot., 48 (1997) 563–569.
[37] S.S. Shim, K. Kawamoto, Enzyme production activity of phanerochaete chrysosporium and degradation of pentachlorophenol in a bioreactor, Water. Res., 36 (2002) 4445–4454.
[38] A. Tomasini, V. Flores, D. Cortés, J. Barrios-González, An isolate of rhizopus nigricans capable of tolerating and removing pentachlorophenol, World. J. Microb. Biot., 17 (2001) 201–205.
[39] H.Y. Kahng, J.J. Kukor, K.H. Oh, Characterization of strain HY99, a novel microorganism capable of aerobic and anaerobic degradation of aniline, Fems. Microbiol. Lett., 190 (2000) 215–221.
[40] N. Chen, S. Chen, L. Chao, L.N. Sun, D.M. Zheng, Q. Liu, Q. Zhang, Study on plant-microbial remediation of antibiotic and heavy metal contaminated soil, Appl. M. Mater., 587–589 (2014) 816–819.
[41] L. Bosso, G. Cristinzio, A comprehensive overview of bacteria and fungi used for pentachlorophenol biodegradation, Rev. Environ. Sci. Bio., 13 (2014) 387–427.
[42] W. Yun, The degradation behavior of pentachlorophenol in the rhizosphere of regress and rhizosphere microecology of fugi. Beijing, China, Chinese Academy of Sciences, 2009.
[43] R.I. Dams, G. Paton, K. Killhan, The effect of rhizosphere on growth of sphingomonas chlorophenolica ATCC 39723 during pentachlorophenol (PCP) biodegradation in batch culture and soil, Biotemas., 19 (2006) 300–314.
[44] T. Günther, U. Dornberger, W. Fritsche, Effect of rye grass on biodegradation of hydrocarbons in soil, Chemosphere, 33 (1996) 203–215.
[45] R. Gupta, V.K. Garg, Vermiremediation and nutrient recovery of non-recyclable paper waste employing Eisenia fetida, J. Hazard. Mater., 162 (2009) 430–439.
[46] B. Wen, Bioavailability of pentachlorophenol to earthworms in artificially contaminated soils, Ecotox. Environ. Safe, 62 (2005) 26–34.
[47] Z. Lin, J. Bai, Z. Zhen, S. Lao, W. Li, Z. Wu, Y. Li, B. Spiro, D. Zhang, Enhancing pentachlorophenol degradation by vermicomposting associated bioremediation, Ecol. Eng., 87 (2016) 288–294.
[48] J. Rodriguez-Campos, L. Dendooven, D. Alvarez-Bernal, S.M. Contreras-Ramos, Potential of earthworms to accelerate removal of organic contaminants from soil: A review, Appl. Soil. Ecol., 79 (2014) 10–25.
[49] X. Li, Z. Lin, C. Luo, J. Bai, Y. Sun, Y. Li, Enhanced microbial degradation of pentachlorophenol from soil in the presence of earthworms: Evidence of functional bacteria using DNA-stable isotope probing, Soil. Biol. Biochem., 81 (2015) 168–177.
[50] X.Y. Hu, B.S. Wen, X.Q. Shan, Bioavailability of phthalate congeners to earthworms (Eisenia fetida) in artificially contaminated soils, J. Environ. Sci. Heal., A., 62 (2005) 26–34.
[51] Y.T. Li, Z. Lin, X.M. Li, P. Cui, L. Xiao, S. Lao, W. Zhang, Effects of earthworm and compost immobilized mode on soil pentachlorophenol degradation by laccase, Ecol. Environ. Sci., 20 (2011) 1739–1744.
[52] Z. Lin, Z. Zhen, Z. Wu, J. Yang, L. Zhong, H. Hu, C. Luo, J. Bai, Y. Li, D. Zhang, Microbial community and enzyme activity of two earthworm species during the bioremediation of pentachlorophenol-contaminated soils, J. Hazard. Mater., 301 (2016) 35–45.
[53] X.Y. Jiang, G.M. Zeng, D.L. Huang, Y. Chen, F. Liu, G.H. Huang, J.B. Li, B.D. Xi, H.L. Liu Remediation of pentachlorophenol-contaminated soil by composting with immobilized Phanerochaete chrysosporium, World. J. Microbiol. Biotechnol., 22 (2006) 909–913.
[54] M.M. And, K.S. Jørgensen, effective and safe composting of chlorophenol-contaminated soil in pilot scale, Environ. Sci. Technol., 31 (1997) 371–378.
[55] R.H. Bentham, N.C. Mcclure, A novel laboratory microcosm for cocomposting of pentachlorophenol contaminated soil, Compost. Sci. Util., 11 (2003) 311–320.
[56] R. Valo, M. Salkinoja-Salonen, Bioreclamation of chlorophenol-contaminated soil by composting, Appl. Microbiol. Biotechnol., 25 (1986) 68–75.
[57] M.M. Laine, K.S. Jorgensen, Straw compost and bioremediated soil as inocula for the bioremediation of chlorophenol-contaminated soil, Appl. Environ. Microbiol., 62 (1996) 1507–1513.
[58] M.D. Bertoldi, G. Vallini, A. Pera, The biology of composting: A review, Waste. Manag. Res., 1 (1983) 157–176.