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Current Problems and Countermeasures of Soil Pollution Management

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Abstract. Soil is a crucial component of the ecosystem and a vital resource for its healthy development. Soil pollution is caused by physiological toxic substances or excess plant nutrients, leading to a deterioration of soil properties and physiological dysfunction in plants. Soil pollution takes various forms, such as chemical, physical, and biological. Based on the primary biological entities involved in the remediation of polluted soil, there are three types of remediation methods: microbial, phytoremediation, and animal-mediated remediation. Among these, microbial and phytoremediation are the most widely used. The remediation of contaminated soil is a complex process involving many factors. The use of a single remediation technique is inevitably constrained and can affect the effectiveness of the remediation. Therefore, the remediation of polluted soil must take into account multiple factors and use a combination of several remediation techniques to develop a comprehensive remediation technique that adapts to the site's soil pollution conditions and conditions, combining the advantages of multiple methods to achieve the ultimate goal of completely restoring the polluted soil.

1 Introduction

The quality of soil is crucial for the healthy development of the ecosystem as it is an important component of the ecological environment and a major resource. Soil contamination is a phenomenon that arises from biochemical toxic substances or excess plant nutrients, leading to deteriorating soil conditions and dysfunctional plant physiology. Soil pollution comes in various forms, including chemical, physical, and biological pollution. However, chemical pollution is in the most common, serious, and complex form of soil pollution [1].

Soil pollution is primarily caused by excessive use of chemical fertilizers and pesticides, as well as industrial emissions of wastewater, waste gas, and solid waste. There is a wide range of soil pollutants, including inorganic substances (e.g., heavy metals, acids, and bases), organic pesticides (e.g., pesticides, fungicides, herbicides), organic waste (e.g., petroleum, polycyclic aromatic hydrocarbon, polychlorinated biphenyl), chemical fertilizers (e.g., nitrogen, phosphorus fertilizers, sludge, slag), radioactive substances, and pathogenic bacteria. Pollutants enter the soil mainly through sewage irrigation, acid rain, automobile exhaust waste, pesticides, and chemical fertilizers, causing serious harm to the soil and posing potential damages to the ecosystem and human health. It is important to determine the sources of soil contamination and implement effective strategies to reduce or eliminate soil pollution [2].

Soil pollution is a hidden and delayed problem. Unlike atmospheric, water, and waste pollution, which can be detected through sensory observation, soil contamination requires analysis and testing of soil samples, as well as the detection of residues in crops, and even studies on its effects on human and animal health [3]. As a result, soil pollution is often overlooked and not easily noticed until it causes significant harm. Additionally, soil pollution is more likely to accumulate than atmospheric and water pollution, as pollutants tend to migrate more easily in the atmosphere and water than in soil. This accumulation makes soil pollution difficult to manage and control, as it is challenging to eliminate pollutants that are difficult to degrade in the soil through dilution and self-purification. Soil pollution requires long-term efforts to reduce its impact on the ecosystem and human health, which can be costly and time-consuming. Treatment techniques such as soil replacement and soil washing may be necessary to recover contaminated soil, and even then, the process may be slow [4].

Soil contamination is a significant problem with various hazards that should not be overlooked. Firstly, it poses a direct threat to water and agricultural produce, and eventually to humans through the food chain. Pollutants can accumulate in plant organisms, enter the food chain, and accumulate in human and animal bodies, leading to serious health risks such as cancer and other diseases. Secondly, soil contamination can cause direct economic losses. Third, soil pollution can also cause other environmental issues, i.e., air pollution, surface water contamination, underground water pollution, and ecological system degradation. When the land is polluted,

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the polluted top soil containing high levels of serious metal can readily get into the air and water body through wind and water force, thus leading to other eco-problems [5].

The continued deterioration of soil quality has significantly impacted global economic and environmental sustainability. Hence, addressing soil pollution has become an urgent issue that requires immediate action. In this article, we will introduce the current status of soil pollution and the methods of soil pollution control.

2 Soil pollution status

Soil is a vital natural resource for both living organisms and humans, as it provides essential elements like water, nutrients, gases and heat are used for plant growth and development. However, because of population growth, industrialization, and improper waste disposal, soil pollution has become a severe problem, resulting in damage and deterioration of soil quality. Soil pollution is mainly categorized into four types: inorganic, organic, radioactive, and biological pollution, with heavy metal pollution being a major component. Additionally, organic pollution, including pathogenic bacteria and antibiotics, has become a growing concern, leading to increased biological pollution.

Contaminated soil contains harmful substances that pose a significant threat to human health and the environment. Therefore, it is crucial to urgently implement soil treatment and remediation to mitigate the risks associated with contaminated soil.

2.1 Inorganic pollutants

Inorganic pollutants present in soil are mainly composed of cadmium, mercury, arsenic, lead, chromium, copper, zinc, selenium, fluorine, and other substances. While many organic pollutants can be biologically, chemically, or physically treated by natural processes to reduce or eliminate their harmfulness, inorganic pollutants have strong enrichment, long retention time, and poor mobility, making their degradation challenging. Inorganic pollution is mainly caused by the use of chemical fertilizers, industrial waste discharge, sewage irrigation, among others [6].

Currently, China's arable land is suffering from the effects of heavy metal pollution caused by cadmium, arsenic, chromium, lead, and other substances, with an area of approximately 120 million hectares, which accounts for approximately one-fifth of the total arable land area. Industrial waste has contaminated 10 million hectares of arable land with "three wastes," and over 3.3 million hectares of farmland are affected by sewage irrigation, leading to extensive soil pollution. The former Ministry of Agriculture reported that the country's annual heavy metal pollution resulted in a reduction of grain production by over 10 million tons and contamination of 12 million tons of food, causing an economic loss of more than 20 billion yuan [7].

2.2 Organic pollutants

Organic contaminants found in soil consist of organic pesticides, benzene, cyanide, oil, synthetic detergents, 3,4-benzopyrene, and microorganisms from municipal sewage, sludge, and stabilized fertilizers. Excessive use of pesticides, industrial waste residues, and the unreasonable piling of urban waste are the primary causes of soil organic pollution [8]. China is among the highest producers and users of pesticides globally, with 666,000 tons produced and 1,312,000 tons used in 1997, averaging 14 kg/ha. In industrial cities, human-made fuel combustion is the primary source of urban soil polycyclic aromatic hydrocarbon, which gradually spread to agricultural soil. The continuous increase in soil organic pollutants is also due to heavy chemical industry, mineral resource development, coal, and oil production. Residues and decomposition products of pesticides, such as phenoxyalkanoates, polycyclic aromatic hydrocarbon, dioxins, tetrachloro-*o*-toluidine, and ethylene thiourea, severely pollute the soil and damage crop quality through bioconcentration in the food chain and food web of the ecosystem, thus posing a threat to human health. Statistics show that about 13-16 million acres of agricultural soil in China are contaminated to varying degrees by pesticides [9].

2.3 Radioactive element pollutants

Radioactive pollutants primarily exist in the areas of nuclear material mining and atmospheric nuclear explosions, including long-lived radioactive elements such as strontium-90 and cesium-137 in the soil. These elements are mainly derived from contaminated sediment and various exhaust gases, wastewater, and waste residue containing radioactive elements. Surface runoff contaminates the soil through the washing of rainwater and waste piles. Once the soil is contaminated with radioactive elements, it is difficult to eliminate them naturally, and the only way to reduce their harmful effects is through natural decay until they become stable elements. Soil contaminated with radioactive elements enters the food chain and causes various diseases, including lung cancer induced by the radiation of radon daughters. In China, approximately 50,000 cases of radon-induced cancer occur annually, which poses a significant threat to human health [10].

2.4 Biological pollutants

Soil biological pollutants consist of disease-causing pathogens and harmful biological populations, primarily originating from untreated human and animal manure fertilization, domestic sewage, garbage, hospital sewage containing pathogens, and industrial wastewater (used for agricultural irrigation or fertilization as a substrate), as well as improperly treated diseased animal carcasses. These pathogenic microorganisms, upon invading and multiplying in soil, pose a high risk of biological contamination and disease spread, while also causing a decline in soil quality and disrupting the original

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ecological balance, thus adversely impacting plants, animals, human health, and the ecosystem at large [11].

3 Soil pollution remediation methods

Contaminated soil remediation can be classified into three types based on different remediation principles: physical remediation, chemical remediation, and biological remediation. Currently, contaminated soil remediation technology has been widely researched and applied for various contaminated sites, including metallurgy and chemical industry, agricultural land, mining areas, and oilfields.

3.1 Physical methods of soil remediation

Physical remediation refers to the technology used to remove or separate pollutants from contaminated soil through physical processes. Common physical methods utilized in soil remediation include soil turning, soil replacement, isolation, heat treatment, and cleaning.

The soil turning method involves moving contaminants from the surface layer of soil to deeper layers, thereby diluting the contaminants. This method is mainly used for deep soil layers. The soil replacement method involves replacing contaminated soil with clean soil, and is commonly used for small areas contaminated with radioactive materials. The isolation method utilizes impermeable materials such as plastic or concrete slabs to prevent the spread of contaminants and to isolate clean soil from contaminated soil [12].

Thermal treatment is the use of heating measures to break down pollutants and later recover them for treatment. The organic pollutants in the soil are vaporized by heating the soil and then the volatile pollutant gases are separated and treated. This technology is currently one of the most advanced contaminated waste treatment technologies in the world. Among them, thermal treatment technology is the main physical remediation technology applied to the site soil organic contamination removal, commonly used include soil vapor leaching, microwave heating, thermal desorption and other technologies. Soil vapor leaching technology can effectively remove volatile organic pollutants from soil. This technique is performed by injecting fresh air into the contaminated area and using a vacuum pump to generate negative pressure, so that when the air flows through the contaminated area, it desorbs and carries the volatile organic pollutants in the soil pores back to the ground via extraction wells. The extracted gas is purified above ground by activated carbon adsorption and biological treatment, and can be discharged to the atmosphere or re-injected into the ground for recycling. The method has the advantages of wide range of organic materials, low cost, standard equipment, high operability, no secondary pollution and no damage to soil structure. The application of this method can achieve 90% removal of light component petroleum hydrocarbon pollutants such as benzene. Thermal desorption technology refers to the process of heating the organic pollution components in the soil through direct or indirect heat exchange, causing them to boil to a high enough temperature to evaporate and separate from the soil medium. Thermal desorption technology has the advantages of reusable soil after remediation, movable equipment, wide range of pollutant treatment, especially for chlorinated organic pollutants such as polychlorinated biphenyl, non-oxidative combustion treatment can significantly reduce the generation of dioxins back. At present, European and American countries have engineered soil thermal desorption technology, which is widely used in the ex-situ or in-situ remediation of organically contaminated soil at high concentration contaminated sites. However, the problems of high price of related equipment, long desorption time and high treatment cost have not been well solved, limiting the application of thermal desorption technology in remediation of POP-contaminated soils. Ultrasonic/microwave heating technology uses the mechanical, thermal and chemical effects of ultrasonic cavitation phenomenon to physically desorb, flocculate and precipitate pollutants and chemically oxidize them, so that they can be desorbed from soil particles and oxidatively degraded to CO_2 and H_2O or environmentally degradable small molecule compounds in the liquid phase. Song et al. showed that ultrasonic waves could not only physically desorb soil organic pollutants, but also completely remove organic pollutants through oxidation. Zhang et al. used ultrasonic waves to purify petroleum-contaminated soil, and the results showed that ultrasonic wave technology could effectively remediate petroleum-contaminated soil [13].

3.2 Chemical methods of soil remediation

The chemical remediation technology of contaminated soil is developed earlier, mainly including soil solidification-stabilization technology, leaching technology, redox technology, photocatalytic degradation technology and electrokinetic remediation technology.

Solidification/Stabilization is a remediation technique that fixes contaminants in the soil and keeps them in a stable state for a long time to prevent or reduce the release of harmful chemicals from contaminated soil. This technology uses chemical, physical or thermodynamic processes to reduce the physical and chemical solubility or environmental activity of contaminants by mixing special additives with contaminated soil. This treatment technology is relatively inexpensive and can greatly reduce the cost of site contamination treatment for some non-sensitive areas of contaminated soil. Commonly used curing/stabilizing agents are fly ash, lime, asphalt and silicate cement, etc., of which cement is the most widely used, the use of cement curing/stabilization of organic and inorganic contaminated soil has been reported internationally, fixed/stabilization technology can handle a variety of complex metal waste, the formation of solids with low toxicity, high stability, disposal costs are also lower, but it requires more equipment, such as spiral rotary wells, mixing equipment, dust collection systems, etc. In addition, the depth of contaminant burial, soil pH and organic matter content can affect the application and effectiveness of the technology to a certain extent.

Curing/stabilization technology has been used for more than 40 years to treat various types of contaminants in the United States, and 30% of the completed U.S. Superfund projects are for source control, with an average operating time of about 1 month, which is much shorter than the operating time of other remediation technologies (e.g., soil vapor extraction, composting, etc.). Curing/stabilization technology is also applied to the remediation of some heavy metal contaminated soils and chromium slag cleaned up dumps in China, and good results have been obtained [14].

Leaching/Extraction is the process of injecting leaching agents such as water or aqueous solutions containing rinsing aids, acid/alkali solutions, complexing agents or surfactants into contaminated soil or sediment to elute the contaminants in the soil. The drenched wastewater is treated and discharged to the standard, and the treated soil can be safely reused. This ex situ remediation technology has been engineered and applied in several countries to remediate heavy metal contamination or multi-pollutant mixed contaminated media. The advantage of drenching/leaching technology over other remediation technologies is that it can be used to treat organic contaminants that are difficult to remove from the soil, such as polychlorinated biphenyl, oils and greases that are easily adsorbed or adhered to the soil, and can be easily removed by solvent leaching technology. This technology uses a lot of water and requires the remediation site to be close to the water source, which increases the cost by treating wastewater. The development of efficient and specific surface solubilizers, the improvement of remediation efficiency, the reduction of equipment and wastewater treatment costs, and the prevention of secondary pollution are important research topics in this technology [15].

Chemical oxidation-reduction technology is used to purify soil by adding chemical oxidants (Fenton reagent, ozone, H_2O_2, $KMnO_4$, etc.) or reducing agents (SO_2, FeO, gaseous H_2S, etc.) to the soil to cause a chemical reaction with pollutants. Chemical oxidation method can be used for remediation of soil and groundwater contaminated with organic pollutants at the same time. The use of the chemical reduction method to remediate reduction-sensitive organic pollutants is a hot topic of current research. For example, the strong dechlorination effect of nano-sized powdered zero-valent iron has been accepted and applied in soil and groundwater remediation. However, the application of zero-valent iron reduction dechlorination for the degradation of chlorinated organic compounds is still subject to problems such as passivation of iron surface activity and polymerization failure by soil adsorption, and new catalysts and surface activation techniques need to be developed [15, 16].

Photo-catalytic degradation is an emerging technology for deep soil oxidation remediation, which can be applied to remediate organic pollutants such as pesticides and other contaminated soils. Soil texture, particle size, iron oxide content, soil moisture, soil pH and soil thickness have obvious effects on the photocatalytic oxidation of organic pollutants, such as high porosity of the soil in the pollutant migration rate, the lower the content of clay particles, the faster photolysis; soil iron oxide plays an important role in regulating the photolysis of organic matter [17].

Electro-kinetic remediation (EKR) is a process in which pollutants are enriched to the electrode zone by driving them through a combination of electrochemical and electrokinetic effects (electro-osmosis, electromigration and electrophoresis, etc.) and then concentrated or separated. That is, by applying DC voltage to both sides of the contaminated soil to form an electric field gradient, the contaminants in the soil are brought to both ends of the electrode by electromigration, electroosmotic flow or electrophoresis under the action of an electric field to remediate the contaminated soil. At present, the electric remediation technology has entered the field remediation application stage, and China has also carried out research on the electric remediation technology of organic contaminated soil such as phenanthrene and pentachlorophenol. The electrokinetic remediation is faster and cheaper, especially for small-scale remediation of mucilaginous soluble organic contaminated soil, which does not require chemical inputs and has almost no negative impact on the environment. However, the electric remediation technology is not effective in removing non-polar organic pollutants that lack charge, and for insoluble organic pollutants, chemical solubilization is required, which is easy to produce secondary pollution [18].

3.3 Biological approaches to soil remediation

Research on remediation technology began in the middle of the 1980s and had successful applications in the 1990s. Broadly speaking, bioremediation technology of contaminated soil means the process of using various organisms in the soil (including vegetation, animals and microbes) to absorb, degrade and transform the contaminants in the soil, so that the content of the contaminants is reduced to acceptable levels or the poisonous and hazardous contaminants are transformed into innocuous materials. According to the different subjects of bioremediation of contaminated soil, it can be divided into three types: microbial remediation, plant remediation and animal restoration, among which microbial remediation and plant remediation are most widely applied [19].

Phytoremediation technology refers to the use of plants to tolerate and over-accumulate certain chemical elements, or the use of plants and their inter-root microbial system to degrade pollutants into non-toxic substances, through the plant in the process of growth of metal elements, organic pollutants and radioactive substances in the environment, such as absorption, degradation, filtration and fixed functions. The technology to purify environmental pollution through the absorption, degradation, filtration and fixation of metal elements, organic pollutants and radioactive substances by plants in the process of growth, including phytouptake remediation using plant hyperaccumulation function, phytostabilization remediation using plant root system to control the spread of pollution and restore ecological functions, phytodegradation remediation using plant metabolism function, phyto-volatilization remediation using plant transformation function and phyto-filtration remediation using plant root system adsorption. Contaminants that can be phytoremediated include heavy metals, agricultural chemicals, oil, POPs, explosion and radio-nuclides. Among them, the phytoremediation technology of contaminated soil has been widely researched, and has been applied to the research and remediation of heavy metals such as arsenic, cadmium, copper, zinc, nickel, lead, etc., as well as the compound contaminated soil with polycyclic aromatic hydrocarbons, and has developed a set of integrated technologies including complex-induced strengthening remediation, combined remediation of different plant sets, and post-remediation plant treatment and disposal. The key to the application of this technology is to select plants with high productivity and high decontamination ability, and to understand the adaptability of plants to soil conditions and ecological environment. In comparison with other remediation technologies, phytoremediation of contaminated soil has many merits, such as low technical cost, low environmental impacts, long-term surface stability, and the ability to remove pollutants from the atmosphere & water bodies around the contaminated soil while eliminating soil pollution, thus contributing to the improvement of the ecological environment [20].

Microbial Remediation is a remediation technology that uses naturally occurring or screened and cultured functional microorganisms (indigenous microorganisms, exogenous microorganisms and genetically engineered bacteria) and promotes or enhances the metabolic functions of microorganisms under artificially optimized and suitable environmental conditions to reduce the activity of toxic pollutants or degrade them into non-toxic substances to remediate contaminated soil. In addition, microorganisms can also be used to remediate contaminated soils by changing the environmental conditions. In addition, microorganisms can also reduce the effectiveness of organic pollutants by changing the physicochemical characteristics of the soil environment, thus indirectly playing a role in remediation of contaminated soil. Usually, a microorganism can degrade a variety of organic pollutants, for example, pseudomonas can degrade dichlorodiphenyltrichloroethane, aldrin, toxaphene and dichlorvos. Therefore, microorganisms have become an important part of the bioremediation technology of contaminated soil and a driving force. At present, microbial remediation research mainly focuses on screening and domestication of specific and efficient degrading microbial strains, improving the activity, longevity and safety of functional microorganisms in soil, as well as optimization of remediation process parameters and regulation of key factors such as nutrients, temperature and moisture. For example, Liu Xianhua et al. used the isolated and screened Pseudomonas aeruginosa AEBL3 to degrade furadan, and found that the content of furadan in the 0-7 cm soil layer reached 90 mg/kg in the non-fungal soil and 48 mg/kg in the fungal soil, with a degradation rate of 96.4%. At present, the research on microbial remediation of organic pollutants has entered the genetic level, and the ability of microorganisms to degrade organic pollutants has been improved by genetic recombination and construction of genetically engineered bacteria. In China, the screening technology of efficient organic pollutant degrading bacteria, the preparation technology of microbial remediation preparation and the field application technology of microbial degradation of organic pollutant residues have been constructed. Jiang JD et al. constructed multifunctional pesticide degrading genetic engineering bacteria CD-mps and CDS-2mpd by homologous recombination method, which could rapidly degrade methyl parathion (MP) within 1-24 h, and furadan could be completely degraded within 30 h [21].

In recent decades, microbial remediation and phytoremediation of contaminated soil have been developed, but animal remediation of contaminated soil has been relatively little studied. Animal remediation (Soil Fauna Remediation) refers to the process of remediating soil pollution through the direct (absorption, transformation and decomposition) or indirect action of soil fauna (improving soil physical and chemical properties, enhancing soil fertility, and promoting the growth of plants and microorganisms). Some large soil animals in the soil, such as earthworms and some rodents, can absorb or enrich the pollutants in the soil, and through their own metabolism, decompose some pollutants into less toxic or non-toxic products. In addition, the soil is rich in small animal species, such as nematodes, elasmobranchs, barnyard mites, centipedes, spiders, and soil wasps, all of which have certain absorption and enrichment effects on soil pollutants and can take away some pollutants from the soil. Kou et al. studied the enrichment of lead by earthworms during the incubation period under different lead concentration gradients in contaminated soils, and the results showed that earthworms had a strong enrichment effect on lead, and the lead content in earthworms increased with the increase of lead concentration. The interaction between bacterial nematodes and soil microorganisms was found to promote the degradation of parathion in contaminated soils. However, there are few studies on the role of soil microfauna in remediation of contaminated soil, and further research on the role of soil microfauna in remediation of contaminated soil is needed [22].

4 Conclusion

Soil safety is crucial for human development. With the development of industry, soil pollution has become increasingly severe due to excessive use of fertilizers and pesticides, industrial emissions of wastewater, exhaust gas, and solid waste. Soil pollution can be roughly divided into four categories: inorganic pollution, organic pollution, radioactive pollution, and biological pollution. Inorganic pollutants have characteristics such as high accumulation, long retention time, difficult degradation, and poor mobility. Soil organic pollutants mainly include organic pesticides, petroleum, synthetic detergents, and microorganisms brought by urban sewage, sludge, and manure. They have characteristics of accumulation, release, and semi-volatility. Radioactive pollutants mainly come from contaminated sediments, as well as various waste gases, waste water, and waste residue containing radioactive elements. Once the soil is contaminated with radioactive elements, it is difficult to eliminate it on its own, and it can only be eliminated when it naturally decays into stable elements and loses its radioactivity. Soil biological pollutants are prone to cause soil biological contamination and spread diseases, as well as cause a decline in soil quality, disrupting the original ecological balance and adversely affecting animals, plants, human health, and the ecosystem. Currently, soil pollution remediation can be divided into three types: physical, chemical, and biological. Physical remediation refers to the technique of removing or separating pollutants from contaminated soil through various physical processes. Common physical methods in soil remediation include tilling, replacement, isolation, heat treatment, and washing. Chemical remediation of contaminated soil mainly includes soil solidification-stabilization technology, leaching technology, oxidation-reduction technology, photocatalytic degradation technology, and electrokinetic remediation technology. Biological remediation is classified into three types based on the different biological remediation subjects of contaminated soil: microbial remediation, plant remediation, and animal remediation, with microbial and plant remediation being the most widely applied.

References

1. W. Zhao, Resource conservation and environmental protection **246** 20 (2022)
2. C. Chen, F. Chen, J. Zeng, et al. Hazards and Control Analysis, Natural Science **10** 7 (2022)
3. Y. Luo, et al. Journal of Xiangtan University: Natural Science Edition **44** 82 (2022)
4. D. Li, Wenyuan Primary School Edition **12** 3428 (2021)
5. J. Ma, et al., Human Health **41** 16 (2022)
6. D. Zhang, et al. Journal of Zhejiang University: Agriculture and Life Science Edition **42** 9 (2016)
7. J. Li, Ecological environment and protection,**3** 14 (2021)
8. Q. Li, et al. Journal of Ecology and Rural Environment, **10** 11 (2021).
9. G. Liu, et al. Jiangsu Agricultural Sciences **50** 27 (2022).
10. J. Tian, et al. Sichuan Environment **26** 4 (2007)
11. C. Trellu, E. Mousset, Y. Pechaud, D. Huguenot, E. V. Hullebusch, G. Esposito, M. A. Oturan, Journal of Hazardous Materials **306** 149 (2016)
12. Z. Cai, X. Zhao, J. Duan, D. Zhao, Z. Lin, Frontiers of Environmental Science & Engineering **14** 5 (2020)
13. K. Tse, S. L. Lo, J. Wang, Environmental Science & Technology **8** 24 (2001)
14. Z. Hao, D. Ma, R. Qiu, Y. Tang, C. Du, Chemical Engineering Journal **313** 60 (2016)
15. M. R. Lasheen, N. S. Ammar, Desalination and Water Treatment, **12** 33 (2016)
16. T. Mattisson, M. Johansson, A. Lyngfelt, Energy & Fuels, **18** 628 (2004)
17. X. Yang, C. Cao, L. Erickson, K. Hohn, R. Maghirang, K. Klabunde, Applied Catalysis B Environmental **91** 657 (2009)
18. G. M. Mutter, Vinegar and Fibers **7** 18 (2017)
19. Q. Wang, D. Zhou, C. Long, Ecology Pedosphere **4** 12 (2014)
20. S. Hemen, Journal of Environmental Science & Technology, **4** 2 (2011)
21. B. Dhal, H. N. Thatoi, N. N. Das, B. D. Pandey, Journal of Hazardous Materials, **30** 272 (2013)
22. L. Wang, D. Yang, F. Ma, G. Wang, R. Chen, Journal of hazardous materials, **5** 435 (2022)