Chapter 8

Soil Pollution and Remediation Approaches

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Abstract

Soil pollution is one of the major threats to the environment in the modern age. As a result of rapid urbanization and industrialization, the soil is being constantly dumped with various organic and inorganic pollutants such as heavy metals, pesticides and fertilizers, petroleum products, polycyclic aromatic hydrocarbon etc. Soil pollution results in hampering the soil physicochemical and biological properties and subsequently reducing the agricultural productivity. The pollutants can also be transferred to other environmental compartments such as water bodies and pollute them as well. Soil pollution can also lead to various health hazards to human beings as well as other animals. Polluted soil can be remediated by a variety of physicochemical and biological

methods and new technologies have further ramped up the process in the past few decades. This chapter aims to give a brief account of the different types of soil pollution as well as their remediation approaches

Keywords: Pollution, remediation, phytoremediation, bioremediation, sustainable remediation

I. INTRODUCTION

Pollution is defined by the introduction of substances, compounds, or energy into the natural environment at levels that disrupt its normal functioning or pose an unacceptable risk to both human populations and other closely interconnected organisms within that environment. Individuals are exposed to potential hazards resulting from contaminated soils, which can occur through skin contact, ingestion, consumption of crops grown in polluted areas, and inhalation of particulates and gases. The ability of soils to support plant life may be compromised due to the toxic impacts of pollutants or disruptions in the biological recycling of essential nutrients. These altered soil conditions also have the capacity to affect the hydrosphere, endangering the quality of drinking water supplies and placing aquatic ecosystems at risk (Scullion, 2006).

Soils, along with water bodies, serve as repositories for a significant portion of the pollutants generated globally. Detecting soil pollution is often delayed due to soil's intrinsic buffering capacity and the uneven distribution of pollutants in the soil. While early instances of soil pollution primarily involved metals and inorganic toxins, there is a growing concern in recent years about organic pollutants. This concern stems from their widespread industrial use as solvents and raw materials, as well as their presence in industrial byproducts. Notably, organic pollutants such as fuel hydrocarbons have emerged as significant contaminants in soil and aquifers. Combustion processes have led to the widespread dispersion of polycyclic aromatic hydrocarbons (PAHs) in soils, contributing to contamination (Scullion, 2006).

A wide array of remediation approaches has been employed to mitigate soil contamination, broadly categorized as physical, chemical, and biological methods. Each of these approaches possesses its own scope of applicability, advantages, and limitations. This chapter aims to compile diverse sources of soil pollutants, their corresponding remediation strategies, the factors influencing the success or failure of these strategies, and potential future directions and perspectives in the realm of soil pollutant removal.

II. TYPES OF SOIL POLLUTION

Soil pollution manifests primarily in two principal forms: natural and anthropogenic. While the predominant share of soil pollution results from human activities, natural catastrophes such as earthquakes and the inherent accumulation of toxic compounds also play a role in soil pollution dynamics. Anthropogenic sources of pollutants can be categorized as either organic or inorganic. Inorganic contaminants, notably heavy metals, constitute a substantial portion of soil pollutants, while organic pollutants encompass a range of substances including pesticides, dyes, petroleum derivatives, and polycyclic aromatic hydrocarbons.

1. Heavy Metals

From a chemical perspective, heavy metals encompass metals and metalloids with atomic masses exceeding 20 and specific gravities surpassing 5. Examples of these include cadmium (Cd), mercury (Hg), copper (Cu), arsenic (As), lead (Pb), chromium (Cr), nickel (Ni), and zinc (Zn). The proliferation of heavy metal contamination has emerged as a significant environmental and food security concern, a consequence of rapid advancements in agriculture and industry, as well as disruptions to the natural ecosystem due to global population growth (Sarwar *et al.*, 2016).

Diverging from organic pollutants, heavy metal pollution is insidious, enduring, and often irreversible. This form of contamination not only degrades the quality of water bodies, the atmosphere, and agricultural produce, but also poses substantial risks to the health and well-being of organisms, including humans, through its bioaccumulation within the food chain (Kankia and Abdulhamid, 2014).

For instance, cadmium (Cd) toxicity leads to a range of detrimental effects at the cellular level, primarily by upsetting oxidant-antioxidant equilibrium. Cd has also been implicated in the development of various conditions including cancer, itai-itai disease, myocardial infarction, peripheral artery disease, hypertension, and diabetic nephropathy (Ghosh and Indra, 2018). Chronic exposure to arsenic (As) results in diverse symptoms such as high blood pressure, neurological disorders, obstetric complications, diabetes mellitus, diseases affecting blood vessels and the respiratory system, along with skin abnormalities like melanosis, leucomelanosis, and keratosis (Rahman *et al.*, 2009). Additionally, lead (Pb) is non-essential to human physiology, and excessive intake can detrimentally affect the nervous, skeletal, enzymatic, endocrine, immune, and circulatory systems (Kankia and Abdulhamid, 2014).

The pervasiveness of soil heavy metal pollution has garnered global attention, primarily driven by concerns over the safety of agricultural produce (Hu *et al.*, 2017). Internationally, there are approximately 5 million sites spanning 500 million hectares of land affected by soil pollution. These areas are tainted with various heavy metals or metalloids, with current soil concentrations surpassing natural geo-baseline levels or established regulatory thresholds (Liu *et al.*, 2018). The cumulative economic toll of global soil heavy metal pollution is estimated to exceed US$10 billion annually (He *et al.*, 2015).

2. Pesticides

Pesticides have long been integral to agriculture, playing a pivotal role in safeguarding crops and livestock from yield losses over several decades. The application of pesticides remains the foremost and widely accepted method to protect plant crops from pest infestations. Nevertheless, only a minute fraction, as low as 1%, of the applied pesticide effectively targets the intended pest. The remaining portion finds its way into the soil, water, and air, subsequently infiltrating the food chain and impacting unintended organisms, including humans, flora, fauna, and soil enzyme systems (Sun *et al.*, 2018).

Significantly, as much as 80 to 90% of pesticides applied to crops directly affect non-target plants, either through direct contact or by drifting and volatilizing from the application site, subsequently contaminating air, soil, and non-target vegetation. Approximately 80% of all applied pesticides are detectable, with half of these residuals manifesting as transformation products (TPs) with persistence exceeding a decade. Notably, 47% of these TPs were identified in Switzerland's top soils where the parent compounds were initially applied.

The ramifications of pesticide contamination pose substantial risks to human health indirectly, through the contamination of the food chain and natural resources. The influence of soil pesticide contamination on agricultural ecosystems reverberates across various dimensions, impacting soil microbial populations, bacterial diversity, nitrogen cycling, soil-dwelling organisms, and soil enzymatic activity. For instance, the fungicide azoxystrobin has been observed to detrimentally impact soil microbial diversity. Pesticides can also infiltrate underground aquifers within cultivated fields. A growing proportion of arable lands, particularly in developing nations like China, exhibit varying degrees of pesticide contamination. According to a 2014 report from the Chinese Ministry of Environmental Protection of Land and Resources, 16% of the surveyed cultivated areas in China were found to be contaminated with heavy metals and pesticides (Sun *et al.*, 2018).

3. Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) arise from the incomplete combustion of organic materials, with the primary anthropogenic source of PAH emissions in natural environments being the utilization of fossil fuels. While numerous PAH compounds occur naturally, only a subset of 16 are designated as priority pollutants due to their environmental significance. PAHs exert considerable health impacts on both human populations and other living organisms, stemming from their carcinogenic, mutagenic, and teratogenic properties. The distinctive attributes of PAHs, characterized by high hydrophobicity and limited water solubility, contribute to their pronounced adsorption onto soils and sediments. This behavior profoundly affects their bioavailability and subsequent degradation processes (Kumar *et al*., 2021).

4. Petroleum Hydrocarbons (PHs)

Petroleum hydrocarbons (PHs) serve as essential raw materials across various industries and as primary sources of energy. However, excessive accumulation of PHs in the environment transforms them into soil pollutants, presenting significant hazards to living organisms. Projections indicate that PH consumption will surge from 85 million barrels in 2016 to approximately 106.6 million barrels by the conclusion of 2030, with usage differing across regions—32% for Europe and Asia, and 53% for the Middle East (Ambaye *et al*., 2022). Petroleum hydrocarbons encompass a range of compounds, including alkanes, cycloalkanes, polycyclic aromatic hydrocarbons, and various other organic pollutants. Their classification as prominent environmental pollutants is attributed to their enduring stability and persistence within the environment. Overabundant employment of petroleum hydrocarbons results in substantial pollution of both water and soil ecosystems. Notably, the spillage of crude oil during offshore drilling, transportation, and onshore transfer has become a recurrent issue worldwide. A primary challenge lies in the intricate composition of crude oil, containing alkanes, aromatic hydrocarbons, resins, and asphaltenes. This complex mixture carries significant toxicity for organisms, owing to its chemical properties, environmental mobility, and pollutant nature.

Understanding the fate of petroleum hydrocarbons in the environment remains an ongoing challenge, with their complete behaviours and impacts yet to be fully elucidated. Consequently, the characterization of petroleum hydrocarbons is a critical element for assessing and predicting their behavior and chemical attributes, as well as their potential long- and short-term consequences on the contaminated environment. This characterization is essential for mitigating animal and human exposure to these contaminants.

III. REMEDIATION APPROACHES FOR SOIL POLLUTION

Remediation approaches encompass three fundamental methods: ex-situ, on-site, and in-situ. In the ex-situ method, contaminated soil is extracted and relocated to an alternative site for treatment. Conversely, on-site involves the excavation and treatment of contaminated soil at its original location prior to reinstatement. In the in-situ approach, treatment transpires directly on-site without soil excavation. The choice of remediation method hinges on the extent of pesticide contamination, whether localized or diffused within agricultural soils.

Historically, ex-situ methods were prevalent for soil remediation, although they carry inherent drawbacks such as elevated expenses associated with soil excavation and transportation, as well as ecological disruption. Consequently, the focus has shifted towards in-situ restoration as a more recent priority. Remediation techniques can be categorized into physical, chemical, and biological categories based on their methodological approach, each possessing distinct applicability, merits, and demerits.

While physical and chemical techniques can be effective for remediating contaminated soil, they are more commonly employed in industrial contexts. Their application to the extensive areas of agriculturally contaminated soil, particularly by organic chemicals, is limited due to high equipment and treatment costs, which may compromise soil's biological and chemical attributes. In contrast, biological methods offer a more sustainable approach, although they may not achieve rapid decontamination over vast areas in a short span. Thus, in numerous scenarios, a hybrid remediation approach that integrates multiple techniques simultaneously often yields the most favourable outcomes.

1. Physical Methods

Physical remediation involves employing physical technologies to reverse or halt soil damage. Techniques encompass soil replacement, isolation, containment methods, and thermal treatments (Yao *et al.*, 2012). Isolation methods commonly include surface capping, landfilling, and encapsulation. Surface capping is an extensively utilized, in-situ approach suitable for areas with elevated contamination levels. This technique is relatively cost-effective and offers robust containment. Nonetheless, its application is constrained to smaller areas, and the loss of agricultural productivity restricts its use in farming regions. Landfilling, a prevalent ex-situ method, facilitates rapid cleanup. However, its adoption on a large scale is limited by high costs and waste disposal requisites. Encapsulation, reserved for radioactive waste, constitutes a specialized technique (Liu *et al.*, 2018).

Subsequent to isolation, contaminants can be eliminated through high-temperature processes like incineration and pyrolysis, or via adsorption. An array of inorganic and organic materials can serve as adsorbents, including clays, activated carbon, zeolites, as well as polymeric substances like cyclodextrins, dendrimers, and hyper-crosslinked polymers.

2. Chemical Methods

Chemical treatments encompass the utilization of agents to induce the conversion of hazardous substances, such as pesticides, into either harmless or less harmful compounds through chemical reactions. The economic costs of chemical remediation can be substantial, particularly depending on the specific matrix being treated. Frequently, chemical remediation is employed in conjunction with physical remediation strategies. An example of a chemical method is advanced oxidation, which operates under normal reaction conditions, thus aligning with environmentally friendly principles. Key oxidants in this method are hydroxyl radicals (Cheng *et al.*, 2016). Another effective oxidizing agent is ultraviolet (UV) radiation, often used in collaboration with hydrogen peroxide or ozone gas. In both scenarios, UV rays expedite the generation of hydroxyl radicals, which are central to the decontamination process (Khan *et al.*, 2004).

Photodegradation and photocatalytic oxidation are also employed for contaminant degradation. In photodegradation, contaminants undergo breakdown either directly due to sunlight exposure or through oxidation by reactive radicals generated from sunlight. Photocatalysis employs semiconductor metal oxides, like TiO_2 and WO_3, as catalysts. These materials are chemically inert, non-toxic, readily available, cost-effective, and exhibit high photoactivity. These semiconductors possess a valence band occupied by stable energy electrons, along with an empty, higher-energy conduction band. The initiation of photocatalysis occurs when radiation is absorbed, leading to the rapid generation of holes in the valence band and electrons in the conduction band, typically on a femtosecond scale. In the presence of water (H_2O) and/or hydroxyl ions, hydroxyl radicals ($\cdot OH$) are formed, along with other reactive radicals like the superoxide radical anion ($O^{2-)}$. Furthermore, electrons can interact with certain contaminants through direct reductive processes (Cheng *et al.*, 2016).

3. Biological Methods

Biological remediation, or bioremediation, stands out as an appealing technology that drives the complete conversion of organic compounds into less harmful end products, typically carbon dioxide (CO_2) and water (H_2O). This approach is recognized for its cost-effectiveness and environmental compatibility in comparison to physical or chemical methods aimed at contaminant removal. Bioremediation can be categorized into microbial bioremediation and phytoremediation, dependent on the type of organisms employed (Nwankwegu and Onwosi 2017).

Three primary techniques constitute microbial bioremediation: enhanced natural attenuation, bioaugmentation, and biostimulation. Enhanced natural attenuation capitalizes on the inherent capabilities of the microorganisms present in the matrix. Bioaugmentation involves the introduction of non-native or genetically modified microorganisms with heightened degradation abilities. Biostimulation, on the other hand, involves the addition of electron acceptors or nutrients to invigorate microbial pollutant degradation (Helbling 2015).

The soil ecosystem harbours a diverse array of microorganisms, numbering in the billions, which play a pivotal role in pollutant breakdown. These microbes utilize organic pesticides as a carbon source, orchestrating their degradation or transformation into non-toxic metabolites. Soil microbial communities are characterized by synergistic or antagonistic interactions among various organisms, rather than a single strain. Among these communities, bacteria, fungi, and actinomycetes emerge as key players in pollutant transformation and degradation. Fungi, in particular, are adept at biotransforming contaminants and other xenobiotics through subtle structural modifications, rendering them non-toxic. The bio-transformed pollutants are then released into the environment, where further degradation processes can take place.

The principal biochemical pathways underlying microbial bioremediation encompass oxidation, reduction, and hydrolysis. Microbial degradation can be naturally achieved by indigenous organisms through the mechanism of natural attenuation. However, when the native microbial capacity falls short, non-native or genetically engineered microorganisms with augmented pesticide degradation capabilities are introduced. In an alternative strategy termed biostimulation, the addition of inorganic and organic amendments such as nutrients and electron acceptors foster an environment conducive to heightened microbial pollutant degradation (Helbling 2015).

Phytoremediation has emerged as a pioneering and promising technology that capitalizes on the intrinsic capacity of plants to remediate various pollutants within diverse environmental contexts, encompassing soil, sediment, groundwater, surface water, and even the atmosphere. This approach has garnered attention due to its cost-effectiveness as an alternative solution for the remediation of contaminated environments. Phytoremediation can be categorized into five distinct processes, each contingent on specific removal mechanisms: phytoextraction, phytodegradation, phytotransformation, phytovolatilization, and rhizoremediation (Yan *et al.*, 2020).

Certain plant species exclusively extract and amass toxicants within their tissues, a phenomenon termed phytoextraction. The enzymatic breakdown of toxicants into non-toxic metabolites occurring within plant tissues is referred to as phytodegradation. When this deactivation process takes place in the soil environment, it is designated as phytotransformation or phytostabilization. Phytovolatilization involves the removal of water-soluble toxicants through transpiration. Rhizoremediation, on the other hand, entails the collaborative efforts of plants and rhizospheric bacteria to eliminate pesticides from the root zone.

The efficacy of phytoremediation hinges on multiple factors, including pesticide properties (such as structure, solubility, concentration), plant attributes (species, age, enzyme profile, exudates), and environmental conditions (moisture levels, pH, temperature, microbiological composition) (Srivastava *et al.*, 2021).

4. Hybrid Technologies

While an extensive range of both conventional and novel techniques has been deployed for soil remediation, none are devoid of limitations. Thus, the combination of two or more approaches for simultaneous pollutant removal from soil has garnered considerable interest in recent times. While these hybrid technologies are more commonly associated with water decontamination, they are equally applicable to soil remediation.

Among the spectrum of hybrid approaches for pollutant removal from soil, nanobioremediation emerges as a particularly potent strategy. It embodies the integration of an initial rapid yet cost-intensive physicochemical technique, succeeded by a subsequent slower but cost-effective biological method. This entails the effective removal of pollutants through consecutive treatments employing both nanoparticles and microorganisms. An exemplar study by Le *et al.* (2015) investigated the degradation of a solution containing Aroclor 1248 (PCB) using nZVI (1000 mg/L), followed by biodegradation with *Burkholderia xenovorans*. Notably, the researchers achieved an 89% degradation of congeners after the nZVI application. Subsequently, a 90% biodegradation of the biphenyls, produced as a result of PCB dichlorination through bacterial metabolism, was observed.

Another integrated nanobioremediation approach was proposed by Singh *et al.* (2013), involving the initial application of Pd/Fe followed by *Sphingomonas* sp. strain NM05 for the degradation of lindane in soil. Their study underscored that this integrated system, or nanobioremediation, exhibited 1.7 to 2.1 times greater efficiency compared to individual systems.

IV. NEW TECHNOLOGIES FOR REMEDIATION OF POLLUTED SOIL

As scientific progress continues to unfold, novel avenues are emerging for remediating polluted soils. As mentioned earlier, hybrid technologies have been explored in depth. Additionally, there are enhanced methodologies, including the utilization of nanoscale zero-valent iron (nZVI). Since its initial synthesis in 1994, nanoscale zero-valent iron (nZVI) has gained prominence as a potent agent for soil remediation, attributable to its robust reducing capabilities and substantial specific surface area. Prior research indicates that in situ remediation employing nZVI surpasses conventional remediation approaches due to its distinctive merits. Over the past decades, diverse synthesis techniques, such as chemical hydrothermal synthesis, precision milling, and electrochemical synthesis, have been developed. Notably, further modifications have been applied to augment the reactivity of freshly prepared nZVI for practical soil remediation, encompassing strategies like doping with transition metals, stabilization using macromolecules or surfactants, and sulfidation. Moreover, nZVI can be synergistically integrated with other techniques, such as bioremediation, to achieve even more effective removal of pollutants. This collaborative approach holds significant promise for the advancement of soil remediation strategies (Li *et al.*, 2020).

The realm of emerging techniques in soil remediation encompasses the electrokinetic remediation (EKR) technology. This method holds substantial promise as a primary separation approach, commonly applied to address contamination in sites affected by both organic and inorganic pollutants. Particularly effective in low permeability porous matrices, EKR stands out as a preferred remediation technology. EKR operates through a synergy of transport mechanisms including electromigration, electroosmosis, and electrophoresis, alongside processes like electrolysis and geochemical reactions. As the emphasis increasingly shifts towards the development of greener synthesis approaches and the integration of EKR into reaction scenarios, the landscape of soil pollution remediation is set to become more dynamic and sustainable (Wen *et al.*, 2020).

Artificial intelligence (AI) stands as a pivotal breakthrough technology in this era, renowned for its multifaceted applications across disciplines. Its potential extends to the realm of remediating polluted soil, holding the promise of a transformative impact. One of the initial hurdles in soil decontamination lies in accurate identification. Soil naturally contains trace amounts of contaminants, rendering their presence not necessarily indicative of pollution until their accumulation reaches a point of harm, posing risks to the environment and human health.

To discern concentration points of pollutants, precise mapping and measurement of distinct contaminant distributions from specific sources are indispensable. Successful mapping and assessment of soil pollution assume paramount importance not only for habitat rejuvenation and human health amelioration but also for sustaining soil quality within an area. However, traditional analytical methods often encounter challenges when it comes to the mapping and measurement of soil pollution. In this era defined by technological prowess, artificial intelligence has emerged as a potent tool. Various AI models hold promise for facilitating soil mapping and the early identification of soil pollution, thus contributing to its effective remediation (Gautam *et al.*, 2023).

V. CONCLUSION

In the backdrop of swift industrialization and urban expansion, the issue of soil pollution has emerged as a pressing concern due to its potential repercussions on human and animal well-being. Consequently, the need for viable solutions through proficient remediation methods has become imperative. Traditional physical and chemical techniques employed to restore and decontaminate polluted soils exhibit significant drawbacks in terms of cost, alteration of soil attributes and native microbial populations, as well as the potential generation of subsequent pollution issues. In contrast, phytoremediation emerges as a more favourable alternative for addressing this challenge. It boasts environmental friendliness and cost-effectiveness, sidestepping the necessity for high-priced machinery and specialized management of tainted locations. Nonetheless, phytoremediation is not without its limitations. Notably, its efficiency in expelling contaminants from sites is comparably protracted in comparison to physical or chemical methodologies. Additionally, its applicability is somewhat confined, demanding a comprehensive understanding of site conditions, contamination specifics, objectives of remediation, efficiency considerations, cost-effectiveness, timeframes, and public acceptance. The advancement of research has fostered the evolution of novel strategies aimed at efficacious and sustainable soil pollution remediation. These strategies are often bolstered by amalgamating various approaches to optimize pollutant removal. However, it is important to note that a majority of these investigations are conducted on a laboratory scale, necessitating further research endeavours to ascertain their viability on a larger, practical scale.

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