Environmental Chemistry Letters (2024) 22:355–371
https://doi.org/10.1007/s10311-023-01663-6

REVIEW ARTICLE

Phytoremediation of contaminants in urban soils: a review

Yachen Zhu[1] · Haiping Gu[1] · Hanyin Li[1] · Su Shiung Lam[2,3] · Meenakshi Verma[4] · Hui Suan Ng[5] · Christian Sonne[6,7] · Rock Keey Liew[2,8] · Wanxi Peng[1]

Received: 16 July 2023 / Accepted: 7 October 2023 / Published online: 4 November 2023

Abstract
Accelerated urbanization has induced the accumulation of toxic substances in urban soils, calling for sustainable remediation methods such as phytoremediation. Here, we review the phytoremediation of contaminants in urban soils with focus on species selection for remediation, mechanisms of remediation, and strategies for enhancing remediation. Plants can remove up to more than 95% of contaminants in soils. The choice of plants varies depends on the specific pollutants present in the soil. For instance, *Bidens pilosa* L. can be utilized to remove cadmium, while *Pelargonium roseum* is effective in removing nickel and lead. The mechanisms of phytoremediation involve absorption, translocation, stabilization, and volatilization of contaminants by plants. The phytoremediation efficiency can be enhanced by the addition of microorganisms, chelating agents, and biochar in soils, and by genetic engineering and nanotechnology.

Keywords Phytoremediation · Remediation efficiency · Microbiological · Green chelate · Foliar spray · Multi-process phytoremediation

Introduction

Social development has unfortunately been accompanied by irreversible natural resource destruction. The pursuit of a higher standard of living leads to the generation of considerable amounts of waste, which has detrimental consequences for the soil environment. The expansion of urban areas encroaches upon previously forested and agricultural lands, thereby exacerbating the problem (Qin et al. 2019; Shabbir et al. 2020). Given the contamination of urban soil and its potential to cause illness, particularly in those with weakened immune systems such as children (Shifaw 2018; Wu et al. 2018), it is paramount to investigate viable solutions to address this issue. Table 1 shows the impact of soil contaminants on human health. Phytoremediation has emerged as a promising approach to address complex and diverse pollutants in urban soil. This technique can play an instrumental role in restoring ecological equilibrium and mitigating the negative effects of urbanization.

Yachen Zhu and Haiping Gu have contributed equally to this work.

✉ Su Shiung Lam
lam@umt.edu.my

✉ Wanxi Peng
pengwanxi@163.com

[1] Henan Province International Collaboration Lab of Forest Resources Utilization, School of Forestry, Henan Agricultural University, Zhengzhou 450002, China

[2] Higher Institution Centre of Excellence (HICoE), Institute of Tropical Aquaculture and Fisheries (AKUATROP), Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia

[3] Center for Global Health Research (CGHR), Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Chennai, India

[4] Department of Chemistry, University Centre for Research and Development, Chandigarh University, Gharuan, Mohali, Punjab, India

[5] Centre for Research and Graduate Studies, University of Cyberjaya, Persiaran Bestari, 63000 Cyberjaya, Selangor, Malaysia

[6] Department of Bioscience, Arctic Research Centre (ARC), Aarhus University, Frederiksborgvej 399, PO Box 358, 4000 Roskilde, Denmark

[7] Sustainability Cluster, School of Engineering, University of Petroleum & Energy Studies, Dehradun, Uttarakhand 248007, India

[8] NV Western PLT, No. 208B, Second Floor, Macalister Road, 10400 Georgetown, Penang, Malaysia

Table 1 Impact of soil contaminants on human health

Pollutants	Sources of exposure	Symptoms	Mechanism(s)	References
Cadmium (Cd)	Cigarettes, food, factories	Emphysema	The increase in cadmium (Cd) caused the downregulation of lysyl oxidase	Zhao et al. (2010), Ganguly et al. (2018)
Lead (Pb)	Mining, paint	Nervous system injury	The activity of pyruvate kinase and creatine kinase was decreased	Lepper et al. (2010), Murgueytio et al. (1998)
Chromium (Cr)	Electroplating, painting	Respiratory system injury	By activating Gli transcription factors and inhibiting autophagy	Huang et al. (2017a, b), Scarselli et al. (2012)
Arsenic (As)	Potable water, food	Skin disease	Change the level of person thioredoxin1	Oberoi et al. (2014), Li et al. (2012)
Benzene (C_6H_6)	Car exhaust, industrial exhaust	Leukaemia	Overall deoxyribonucleic acid (DNA) hypomethylation	Ji et al. (2010)
Bisphenol A	Plastic product	Reproductive system problems	Decrease serum testosterone concentration	Zhang et al. (2023)
Polyaromatic hydrocarbons Gli transcription factors	Automobile exhaust	Cutaneous inflammation	Aryl-hydrocarbon receptor mediated transcription is activated	Tauchi et al. (2005)

Certain heavy metals can potentially harm soil environments and negatively impact metabolic functions even in small quantities (Antoniadis et al. 2021; Kumar et al. 2022; Qin et al. 2021). Urban soil pollution is primarily caused by organic pollutants such as pesticides that are mainly derived from agricultural land. Soil ecosystems can be disrupted by pesticides, resulting in potentially harmful consequences (Table 1). As these pollutants travel through the food chain, they can be transferred directly or indirectly to humans (Rajmohan et al. 2020).

Understanding the sources of contaminants in urban soil is crucial for remediating soil pollution and ensuring a healthy environment for citizens. These contaminants can either be human-made or caused by natural disasters. However, urban soil pollution is mainly anthropogenic (Shifaw 2018), resulting from a combination of “three wastes” generated by factories, direct discharge of sewage, pesticide use, smelting operations of high metal ores, burning fossil fuels, and leaching from municipal waste landfills (Sharma 2021). Certain contaminants such as pesticides, heavy metals, and emissions from manufacturing plants (Fig. 1) pose a significant threat to urban soil health. It has been observed that the soil in urban areas still contains traces of pollutants, specifically heavy metals and non-biodegradable pesticides. However, stringent government regulations have been enacted to address this issue and efforts have been made to effectively control anthropogenic emissions to mitigate the impact of these harmful substances.

Numerous elements present in soil can be toxic to living organisms with heavy metals being the most prevalent and harmful (Antoniadis et al. 2021; Wieczorek et al. 2020). Inorganic pollutants are particularly challenging to degrade using chemical induction methods due to their unique properties (Khalid et al. 2017). Quasi and trace metals can accumulate to dangerous concentrations in soil due to various factors, including the rapid expansion of the industrial sector, municipal waste, disposal of high metal wastes, pesticides, coal combustion residues, tailings, lead-free gasoline, paint, synthetic fertilizers, wastewater and manure discharges, irrigation, petrochemical spills, atmospheric deposition, and sewage sludge (Haider et al. 2021). Heavy metal pollutants in soil have been identified as significant contributor to soil pollution (Qin et al. 2021). Additionally, biological solids represent another source of soil pollution that may contain various forms of toxic elements (Antoniadis et al. 2021; Ashraf et al. 2019; Rinklebe et al. 2020; Shaheen et al. 2020; Tayang and Songachan 2021; Wang et al. 2020a, b). Heavy metal pollution typically stems from urban soil mining and oil processing activities. As cities continue to expand, urban soils often contain a combination of contaminated materials with varying characteristics, including fertilizers and pesticides, resulting from a combination of natural and man-made substances. It was revealed that anthropogenic sources often surpass geological and soil sources in terms of metal loads, with soil abundances and contamination levels exhibiting significant differences (Sodango et al. 2018; Wieczorek et al. 2020). Other factors such as urban transportation emissions and different land uses may also contribute to soil pollution (Liu et al. 2016).

The issue of heavy metal pollution is a serious concern for environmental health especially toxic elements such as lead (Pb) and arsenic (As). Arsenic and its derivatives are

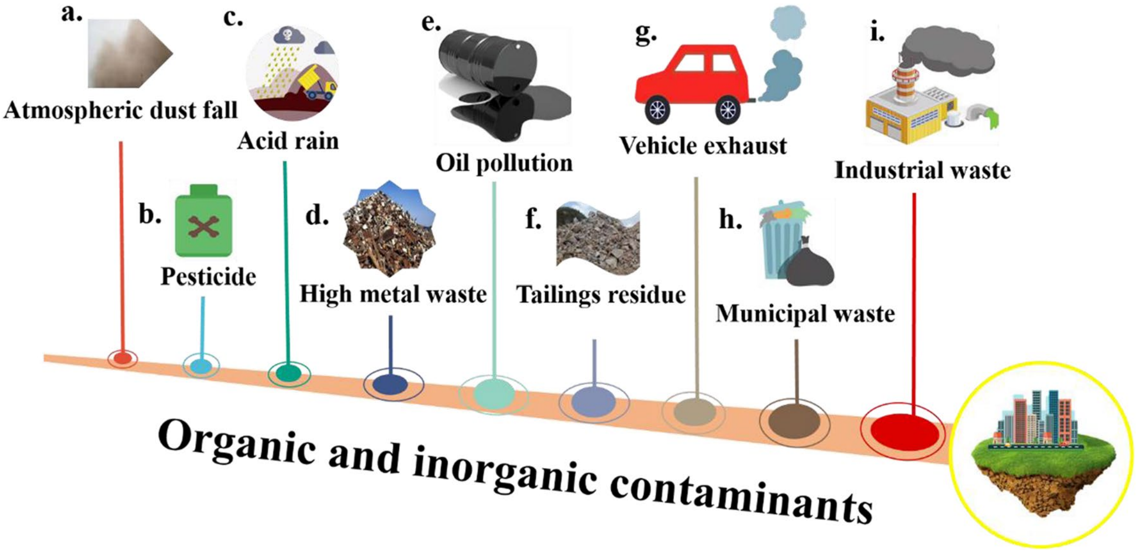

Fig. 1 Urban soil pollution is caused by various sources, with persistent organic pollutants and toxic elements being the most prominent. The sources of these pollutants are represented by symbols **a–h** in the accompanying figure

listed as the primary human carcinogens that capable of disrupting the human genetic structure and leading to severe physical ailments (Abbas et al. 2018). Inorganic arsenic poisoning has significant health impacts including cancer and other diseases affecting multiple body organs (Alka et al. 2021; Souri et al. 2020). Lead (Pb) is recognized as a hazardous element present in urban soil that poses a risk to human health (Zajecka and Swiercz 2021). Exposure to lead (Pb) can result in a range of adverse effects including reduced mobility and memory loss, impaired learning and work performance, and hearing impairment due to neurotoxicity. International attention was given to the Hunan blood lead (Pb) incident in China, which affected more than 300 children with elevated blood lead (Pb) levels (Sharma et al. 2018). Moreover, the issue of soil contamination with lead (Pb) has been a longstanding concern for many stakeholders (Li et al. 2016). In addition to lead (Pb), other heavy metals like copper (Cu), cadmium (Cd), chromium (Cr), mercury (Hg), and nickel (Ni) are also commonly found in urban soil, leading to soil degradation and posing a serious health risk to humans (Usman et al. 2020).

Various organic pollutants can be found in urban soil including pesticides, fertilizers, herbicides, fungicides, and flame retardants (Chang et al. 2022; Lucas et al. 2021). It is worth noting that residues of organochlorine pesticides remain prevalent in the environment (Song et al. 2020). The urban soil may also contain pollutants such as petroleum, polychlorinated biphenyls, phenols, and industrial waste. These organic pollutants can be found in various sources including wastewater treatment plants, biosolids, and firefighting foam (Bolan et al. 2021). Specifically, removing fluorinated organic chemicals from soils contaminated with polyfluoroalkyl substances can be a very challenging task (Kumar et al. 2022). The determination of total petroleum hydrocarbons in a mixed state involves the analysis of various hydrocarbons that are highly refractory and widely spread globally (Patowary et al. 2017). The presence of benzene, phenols, long-chain hydrocarbons (C10–C40), and polycyclic aromatic hydrocarbons makes the pollutant complex and challenging to manage. Additionally, the composition of alkane, olefin, alkyne, aromatic hydrocarbons, and other substances that are difficult to decompose influences the persistence of total petroleum hydrocarbons (Hoang et al. 2021; Truskewycz et al. 2019). Polycyclic aromatic hydrocarbons are characterized by their multiple dense aromatic rings, which are commonly found in sediments, the atmosphere, water, and soil. These hydrocarbons have garnered significant attention from the scientific community in recent decades due to their prevalence as soil pollutants (Zhang and Chen 2017). As urban development continues, plastic waste has also become a significant source of soil pollution. Microplastics are particularly problematic as they pose a more serious threat to the environment and human health than conventional plastics. These microplastics have been detected in the atmosphere, ocean, and soil and have the potential to cause tumors, chronic diseases, and other harmful symptoms if ingested by humans (Birch et al. 2020; Chia et al. 2021).

Urban soil remediation techniques

Various soil remediation techniques are currently available including physical, chemical, chemical bioremediation, and biological techniques (Al Chami et al. 2015). Physical remediation techniques include thermal treatment, soil replacement methods, electrical remediation, vitrification techniques, and soil washing. The thermal treatment eliminates soil contaminants by subjecting them to high temperatures, which causes them to vaporize. The resulting vapors are then slowly condensed and solidified through a recovery process. This method effectively decomposes soil pollutants by exposing them to elevated temperatures. Additionally, thermal desorption can also be achieved at lower temperatures (Ashraf et al. 2019; Zhang et al. 2017). Thermal remediation allows greater control of operating parameters such as heating time and temperature. This provides rapid removal of contaminants, enhanced mobility, and minimization of contaminant toxicity. However, this method requires more infrastructure and machinery, resulting in increased costs and changes in soil properties (O'Brien et al. 2018). Additionally, excessively high or low temperatures can destroy humus in the soil and reduce its ability to retain fertilizers (Sharma et al. 2018).

Soil replacement involves replacing contaminated soil with healthy soil or diluting pollutant concentrations. A key principle underlying this method is to minimize the impact of pollutants on the surrounding environment by isolating contaminated soil. While soil replacement methods are effective, they are often costly and typically applied to smaller areas of highly contaminated soil (Sharma et al. 2018). Electrical repair is a remediation technique that follows electrodynamic principles, whereby an electric current is introduced to the contaminated area to confine the pollutants near the electrodes for recovery. Electroremediation is a viable option for removing pollutants from low-permeability clays or sediments. This process involves breaking down, mineralizing and moving contaminants as well as boasting shorter intervals. Electroremediation techniques are particularly suitable for clay and chalky soils, complexes, and the simultaneous removal of other soil pollutants. However, it is important to note that waste disposal and the movement of insoluble and chelated compounds remain significant disadvantages of this technique (He et al. 2015; Wang et al. 2020a, b). Furthermore, in situ electrokinetic techniques have improved efficiency in removing contaminants from field soils with surfactants, co-solvents, and solubilizers like cyclodextrins (Kuppusamy et al. 2017).

Vitrification is a thermal treatment process that involves the liquefaction of soil contaminants followed by rapid solidification. The resulting glassy solid vitrification product can effectively trap and immobilize contaminants, thereby isolating them from the surrounding environment (Sharma et al. 2018). Vitrification is well-suited for treating soils with low metal concentrations (He et al. 2015). Soil washing has emerged as a promising remediation technique for soils contaminated with high molecular weight polycyclic aromatic hydrocarbons (Kuppusamy et al. 2017). The development of alternative detergents that are more environmentally and economically friendly for soil rinsing has garnered significant interest. The objective is to enhance soil contaminant removal efficiency while also considering specific characteristics of the treated soil. Despite its proven efficacy, soil washing has the potential to generate secondary liquid waste and potentially lead to recontamination (Gusiatin et al. 2020).

Soil amendments utilizing chemical methods involve the application of cement, silica, and lime to decrease the solubility of pollutants in the soil. As a result, pollutants are effectively sealed within the soil, stabilizing it and making it easier for heavy metals to be restored, particularly chromium (Cr). Research findings indicate that calcined bird clam shells combined with lime can effectively fix heavy metals in soil. Additionally, studies have shown that calcined cockle shells could serve as a low-cost soil amendment (Islam et al. 2017). The chemical immobilization of a contaminant involves precipitating or adsorbing the mobile portion of the contaminant using chemical reagents. This process, also known as “in situ” stabilization, is designed to immobilize or capture the contaminant. Alternatively, chemical fixation involves integrating the contaminant into the underlying structure rather than utilizing the soil to repair it. This can be achieved by adding a binder to the contaminated soil, which renders it into solid chunks (Rajendran et al. 2022). For instance, straw and fly ash mixtures have proven effective in stabilizing metals (Hu et al. 2014). Pollutants can be limited by chemical fixation, but they cannot be eliminated. Moreover, the possibility of removing captured contaminants becomes less viable once external factors damage the solid block (El-Naggar et al. 2018; Khan et al. 2021).

There is extensive research on using physicochemical methods for treating soil and wastewater contaminated by various pollutants. Among these methods, ion exchange has been identified as a therapeutic approach to physical–chemical processes (Alka et al. 2021). This process involves the exchange of pollutant cations and anion ions in the soil, which has proven to be an effective means of treating wastewater pollutants. However, it should be noted that not all pollutants require ion exchange treatment, particularly heavy metals that do not pollute the soil. In such instances, remediation of co-contaminated soils can be achieved by exchanging cations with other matching matrix solutions, thereby maintaining the charge transfer balance. Studies have shown that natural zeolites are highly effective at facilitating the exchange of various contaminants, including copper (Cu), cobalt (Co), zinc (Zn), and manganese (Mn), across two or more contaminated environments. While synthetic resin is often utilized as a substrate in this process through organic ion exchange, there are certain drawbacks associated with this method, such as pH sensitivity and membrane contamination (Rajendran et al. 2022). Therefore, natural zeolites have been favored in various studies due to their superior ion exchange capacity and stability.

The ultrasonic treatment process in acidic solvents to remove pollutants from the soil is commonly referred to as leaching. This technique involves using ultrasonic waves to break apart soil particles, which results in the dispersion of pollutants from the soil into the acidic solution. While these methods may effectively solve the problem quickly and temporarily, they are often accompanied by high costs, damage to soil properties, and the potential for secondary pollution (Ali et al. 2013; Ullah et al. 2015). Remediation of contaminated soils has been made possible through physical-biological approaches, which integrate both physical and biological methods. Various techniques have been developed to effectively eliminate heavy metal pollutants from soil, including bioelectrical and bioleaching methods. Recent studies demonstrate that the long-term application of bioelectrical and bioleaching techniques can efficiently detoxify soil contaminants (Huang et al. 2017a, b). Biological adsorption is a passive technique that utilizes organisms to remove pollutants from the environment efficiently. This method offers several advantages over other approaches, including stabilizing and enhancing biomass performance when encapsulated, as well as its reusability and potential for large-scale applications. The immobilization of microbial biomass in a polymer matrix also provides added benefits such as increased rigidity, heat resistance, and optimal porosity for practical use. As a result, immobilization techniques that effectively eliminate residual pollutants from soil and improve industrial wastewater treatment efficiency are gaining popularity (Sharma et al. 2018).

Bioremediation methods utilizing solar energy and preserving natural soil characteristics (Ullah et al. 2015) are increasingly recognized as a more promising approach to pollution control than other methods due to their cost-effectiveness, efficiency, and safety (Kuppusamy et al. 2017; Sodango et al. 2018). This technique involves microbial and phytoremediation, with microbial remediation being a particularly significant environmentally friendly method for managing soil pollution and fostering a sustainable environment. As microorganisms degrade pollutants, they acquire energy for metabolism and carbon, which are essential components of all cell structures (Varjani 2017). Microbial remediation operates on the principle of absorbing, oxidizing, and recovering pollutants in the soil through life structures, inhalation, biological conversion, metabolism, and ultimately eliminating or diluting pollutants. Microorganisms possess a robust metabolic function, enabling them to function as catalysts for transforming soil pollutants. Extensive research has demonstrated that these microorganisms can endure extremely harsh environmental conditions, such as contaminated soil, and convert soil contaminants into non-toxic forms. As a result, microorganisms play a vital role in controlling soil pollutants and recovering biological adsorbents from the soil. Various biosorbents, including algal, bacterial, and fungal, have been demonstrated to eliminate heavy metal contaminants from soil, with algae displaying superior adsorption capabilities (Ubando et al. 2021). Microbial adsorption of pollutants is considered a promising approach for treating contaminated soil without secondary pollution (Sodango et al. 2018). Specifically, *Micrococcus luteus* and *Chromolaena odorata* have proven to be effective in bacteria-assisted phytoremediation of mixed polluted soil under saline-alkali soil conditions, as they tolerate heavy metals, petroleum, and saline-alkali soil (Jampasri et al. 2020).

Phytoremediation has emerged as a promising eco-friendly approach that offers numerous benefits in the remediation of extensive areas of soil contaminated with harmful substances, particularly heavy metals. This method entails utilizing plants that absorb contaminants from the soil and neutralize their toxic effects by converting them into non-toxic compounds (Khan et al. 2022). Consequently, accumulated pollutants can be removed through various physicochemical or biological techniques. The growth of plants has a significant impact on the physical and chemical characteristics of the soil. Plant roots create channels facilitating water and air penetration, enhancing soil fertility and alleviating soil stress (Gerhardt et al. 2017). This process is crucial in restoring microbial communities with minimal nutrient inputs, thus conserving valuable resources (Alka et al. 2021). Phytoremediation employs specific plant species to accumulate or degrade pollutants in the soil, which can effectively purify soil pollutants (Gavrilescu 2022). The biomass generated during this process has numerous benefits, including fertilizer and biofuel cogeneration, which positively impact health, the environment, and cost management (Cristaldi et al. 2017). It was found that plants remove up to 97% of the atrazine and organic hydrocarbons from the soil, thus providing a sustainable and effective approach to soil remediation (Wei et al. 2021).

The metabolic processes of plants enable them to remove, purify, and decompose organic pollutants continuously from the soil. The rhizosphere microorganisms are thus provided with energy and their activities are stimulated by this approach. Phytoremediation effectively removes soil organic pollutants, but its efficiency varies depending on the location of contamination, which necessitates a variety of plant options. The phytoremediation process involves converting organic pollutants into a non-hazardous form that is safe for the environment and human health, thereby avoiding secondary pollution (Wei et al. 2021). Furthermore, plant roots can take up ionic compounds, creating an inter-root ecosystem that contributes to biological efficacy and soil fertility (Yan et al. 2020). In contrast to traditional remediation techniques, phytoremediation facilitates the conservation of soil biospheres and quality changes while adhering to environmental laws and regulations. Moreover, phytoremediation costs significantly less than other technologies (Liu et al. 2018).

Selection of phytoremediation species

Phytoremediation is an effective soil conservation technique that protects structural integrity and properties from potential harm (He et al. 2015). The success of phytoremediation depends on selecting appropriate plant species with the necessary traits, such as pollution tolerance, rapid growth, and significant biomass (Gerhardt et al. 2017). The suitability of a plant for phytoremediation is determined by its ability to thrive in contaminated soil, as outlined in Table 2. However, not all plant species can serve this purpose, and only highly enriched and tolerant plants are suitable for this process (Gavrilescu 2022). The vesicle plays a critical role in storing contaminant ions within the hyper-enrichment apparatus. The compartmentalization of the vesicular zone is a crucial criterion for screening super-enriched plants and is considered an essential mechanism for plant enrichment (Guan et al. 2018). Additionally, microorganisms or plant metabolites can enhance phytoremediation by directly degrading certain volatile polycyclic aromatic hydrocarbons, phenols, and other pesticide components (Gerhardt et al. 2017; Henner et al. 1999). Table 2 presents a list of plants with potential urban soil remediation.

Mechanisms of soil remediation by plants

Chelating compounds have gained widespread usage due to their efficacy in improving various processes (Yan et al. 2020). Specifically, chelating compounds have been employed as enhancers to expedite certain processes (Angulo-Bejarano et al. 2021). Organic amendments can mobilize contaminants in soil. The addition of these amendments leads to the transfer of contaminants to the solution, thereby increasing their mobility (Kumar et al. 2022). Plant hormones are vital as endogenous molecules that modify physiological and molecular responses and are essential for plant survival under pollutant stress. Plant hormones can stimulate enzyme activity, alter plant characteristics, and regulate reproductive capacity even at low concentrations (Fig. 2). For instance, abscisic acid can function under unfavorable conditions, thus supporting plant survival (Sytar et al. 2019).

Uptake of pollutants by plants

The process of pollutant absorption by plants is reliant on the bioavailability of pollutants in the root zone. The root system is the primary entry point for pollutants to infiltrate plants. Plant root metabolites provide nutrients to soil microorganisms and other beneficial substances (Li et al. 2020). When contaminants infiltrate the root cell, they may bind with various chelating agents to form complexes. These complexes including precipitated carbonates, sulfates, and phosphates, become immobilized in specific regions with the vesicle being one such storage location (Ali et al. 2013; Sharma 2021). Pollutant uptake occurs through root cells (Angulo-Bejarano et al. 2021), while root hairs provide adequate space for contaminants to accumulate. Additionally,

Table 2 Plants with potential for urban soil remediation

Pollutants	Plant species	Soil/water	Accumulation (dry weight)/removal rate (%)	References
Cadmium (Cd)	*Bidens pilosa L*	Soil	405.91 mg g^{-1}	Dai et al. (2017)
Cadmium (Cd)	*Bidens pilosa L*	Water	1651.68 mg g^{-1}	Dai et al. (2017)
Cadmium (Cd)	*Miscanthus sinensis*	Water	10.796 mg g^{-1}	Guo et al. (2016)
Cadmium (Cd)	*Chamaecrista fasciculata*	Soil	2.3156 mg g^{-1}	Henson et al. (2013)
Mercury (Hg)	*Lupinus albus L*	Soil	4550 μg g^{-1}	Quinones et al. (2021)
Mercury (Hg)	Cyrtomium macrophyllum	Soil	36.44 mg kg^{-1}	Xun et al. (2017)
Nickel (Ni)	*Pelargonium roseum*	Soil	30,994 mg kg^{-1}	Mahdieh et al. (2013)
Lead (Pb)	*Pelargonium roseum*	Soil	90,982 mg kg^{-1}	Mahdieh et al. (2013)
Cadmium (Cd)	*Crassocephalum crepidioides*	Soil	291.2 mg kg^{-1}	Zhu et al. (2022)
Chromium (Cr)	*Nopalea cochenillifera*	Soil	25,263.396 ± 1722.672 mg kg^{-1}	Adki et al. (2013)
Benzene, toluene, ethylbenzene and xylenes (BTEX)	*Canna × generalis*	Soil	21% BTEX in 80 days	Boonsaner et al. (2011)

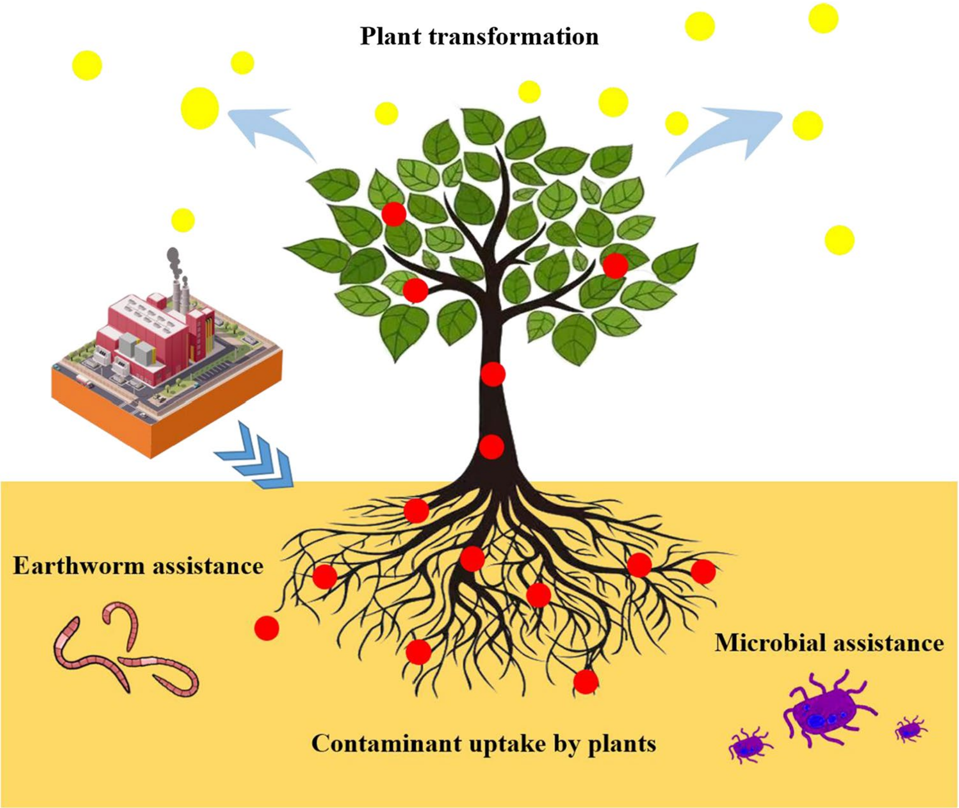

Fig. 2 Soil contamination caused by human activities in urban areas is a significant environmental concern. Fortunately, an eco-friendly solution called phytoremediation utilizes plants to remove pollutants from the soil. This process involves plants taking up contaminants through their roots, then storing and converting them into non-toxic substances. The red dots in the illustration represent pollutants, while the yellow dots indicate contaminants converted into non-toxic forms. This method is effective and sustainable, making it an ideal solution for soil remediation

contaminants can combine with root metabolites to form ligands that facilitate their entry into the root epidermis. This is critical for pollutant translocation across the root plasma membrane (Bartoli et al. 2018). It has been observed that plants can adsorb pollutants to the root skin and cross the cell membrane into the root cell. Furthermore, root secretions bind to or precipitate soil pollutants, enabling them to adsorb on the soil surface (Yan et al. 2020). These complexes comprise various chemical forms such as carbonates, sulfates, and phosphate precipitates, with different root secretions exhibiting distinct adsorption patterns for pollutants (Yang et al. 2021). Metal ions can become anchored in the extraplasmic cell wall or the coplasmic compartment, where they are subsequently isolated within a vesicle. From there, they can be translocated into the stela and ultimately transferred to the branch via the xylem vessels, following their passage through the root coplasm and the xylem stream (Yan et al. 2020).

When plants receive signals indicating the presence of heavy metal, they activate defense mechanisms by releasing organic acids derived from mitochondria. These acids then form complexes with metal ions outside the root cell. Additionally, transporter proteins within the roots facilitate heavy metal absorption. An example is the arsenate absorption by *Arabidopsis* roots through a phosphate transporter (Castrillo et al. 2013; Kamiya et al. 2013; Zhao et al. 2022). Contaminant ions bind to protein chelators within the cytoplasmic environment, forming complexes that are transported to vesicles and other apparatus by transporters. Transport proteins enable contaminants in the soil to be carried to the xylem, eventually reaching the branches. They may also be introduced into the cytosol, golgi, and chloroplasts via transport proteins (Fig. 3) (Angulo-Bejarano et al. 2021; Kikkert and Berkelaar 2013).

Selenium absorption by plants varies across different soil types. The two primary bioavailable forms of selenium (Se) in soil are SeO_4^{2-} and SeO_3^{2-}. In environments where oxygen is abundant, SeO_4^{2-} is the predominant form of selenium, whereas SeO_3^{2-} is more commonly found in areas with limited oxygen. Furthermore, certain soils may contain organic compounds, such as selenium and amino acids (El Mehdawi et al. 2015), which can be readily absorbed by plant root systems (Kikkert and Berkelaar 2013). Plant roots can uptake both selenite and selenate ions. The absorption of selenate occurs via sulfate transporter proteins, while selenite is absorbed through phosphate transporter proteins and water channel proteins (Schiavon and Pilon-Smits 2017). Despite rapid metabolism after ingestion, selenite remains throughout the plant (Trippe and Pilon-Smits 2021). Plants with a low bioaccumulation capacity tend to retain these ions predominantly in root vesicles while highly accumulating plants rely on vacuum transport proteins to transfer heavy metals and immobilize them in leaf vesicles (Gavrilescu 2022; Kosakivska et al. 2021; Sharma et al. 2016). During

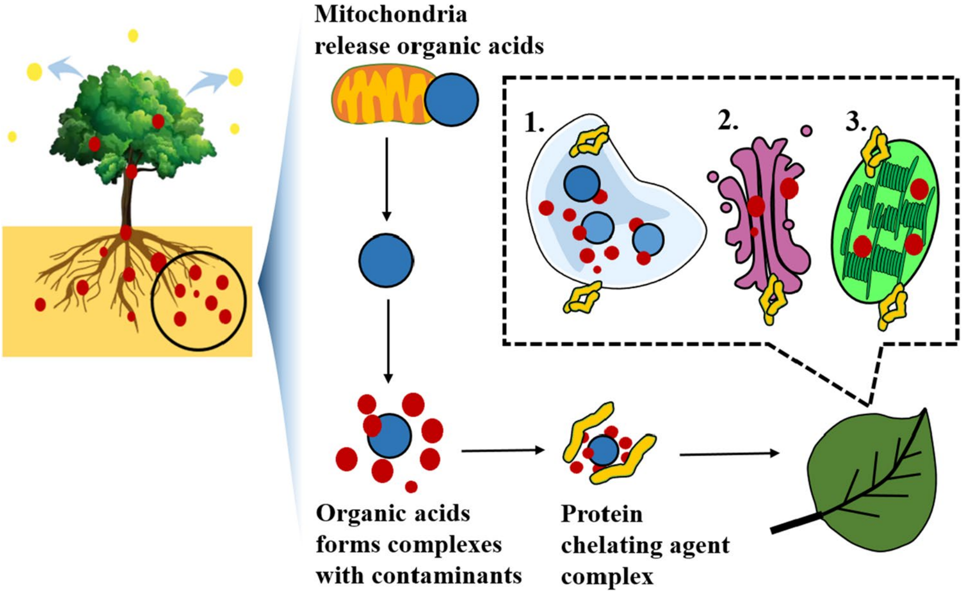

Fig. 3 The process of uptake and transportation in plants is a crucial mechanism that enables them to absorb and retain nutrients and other substances, including pollutants in the soil. The red dots in the figures represent pollutants in the soil, and the blue dots represent organic acids. The numbers **1–3** denote the key structures involved in the process, namely vacuoles, golgi apparatus, and chlorophyll. These structures play a pivotal role in storing pollutants by transporting chelators and other substances, thereby contributing to the overall health and well-being of the plant

this process, metal ions are temporarily stored in the cytoplasm before being transferred upwards through effective xylem mechanisms to disperse throughout stems, leaves, and other organs, and ultimately separated into ions (Gavrilescu 2022). The amino acids present in cytosine contribute to the detoxification of soil contaminants via phytochelin (Sharma et al. 2021).

Transport and transfer by plants

Plant contamination is usually mediated by molecular transduction and the transport of proteins and coordination compounds. Root membrane transporters in plants play a crucial role in absorbing pollutants from the soil. For instance, heavy metals are absorbed by the roots of plants and subsequently distributed to various organs via carrier proliferation, symbiotic relationships, or transmembrane carriers (Gerhardt et al. 2017). Compounds are also transported between cells via plasma processing in the symbiotic pathway. Moreover, the vascular system of plants is essential in pollutant transportation and can work in conjunction with transporters (Manoj et al. 2020). In the transcellular transport process, pollutants are transmitted through neighboring cell membranes, and some plant species can facilitate this process with transport proteins (Alka et al. 2021; Banda et al. 2019; Fujita and Inui 2021), enabling pollutants to be transported to other locations (DalCorso et al. 2019). Effective transport of pollutants from roots to buds is essential to transfer contaminants from underground to above ground (Zhao et al. 2022). Transport enzymes play a crucial role in transporting heavy metals, including maintaining metal state stability. Overexpression of the HMA4 gene has been shown to increase cadmium (Cd) and zinc (Zn) efflux from root coplasm to xylem vessels, thereby promoting metal tolerance. The addition of another set of transport proteins significantly enhances the stability of cadmium (Cd) and zinc (Zn) states, further promoting their tolerance. Vesicles located in cysts and plasmates are also related to plant tolerance for pollutants and accumulation extent. Furthermore, natural resistance-related macrophages and other transport mechanisms are involved in the transportation of pollutants (Angulo-Bejarano et al. 2021; Girdhar et al. 2014; Yan et al. 2020).

Plants can transfer organic pollutants to their aerial parts through the cohesive forces of water within their xylem vessels. In addition, the phloem produces wood pieces, phlotin acids, and alkalinity. The xylem vessels are particularly significant due to their ability to combine with organic pollutants under acidic conditions (Fujita and Inui 2021). Upon entering the plant root system, pollutants form compounds with organic acids and other chelating agents to be fixed in the extracellular cell wall or intracellular space. These pollutant ions isolated within the vesicles will translocate through the root of the xylem stream and are subsequently transferred to the branch in the xylem stream, where they are transported and distributed in the leaf through the extraplastid or coplasmic body. Finally, they are separated by the extracellular or cooriginal body in the plant vacuole to prevent accumulation in the solution (Bastow et al. 2018; Yan et al. 2020). The highest accumulation of pollutants is found in roots followed by stems and leaves (Marrugo-Negrete et al. 2016). Studies have shown that the cortex and leaf meat tissue are the main accumulators of cadmium (Cd), which is primarily found in vesicles (Yang et al. 2021).

Plant detoxification and transformation

Phytoremediation is an important process in which plants are used to detoxify organic pollutants and heavy metals. Studies have shown that various low molecular weight organic acids, such as oxalic acid, can be leached from plants particularly those associated with agriculture in the presence of harmful pollutants. This chelates pollutants and mitigates plant damage (Ma et al. 2016a, b). Plant vesicles contain metallothionein, glutathione, oxalic acid, and citric acid, which play a crucial role in managing the harmful effects of pollutants on plant cells (Guo et al. 2012). There are two primary approaches to controlling the adverse impact of pollutants on plants: avoidance and tolerance mechanisms. Various strategies have been employed to achieve this such as limiting the uptake of pollutants and restricting their movement through root cells to plant tissues (Yasseen and Al-Thani 2022). In case of an excess accumulation of pollutants in the cytoplasmic lysate, plants adapt by chelating and reducing the pollutant concentration to a relatively low level (Yan et al. 2020).

Certain plant species contain free amino acids that serve as osmotic pressure regulators, facilitating the reduction in toxic pollutants and their associated toxicity levels (Kocaman 2022; Li et al. 2022; Lwalaba et al. 2020; Okunev 2019). Glutathione and glutathione-S-transferase have been identified as effective detoxification agents in plant roots contaminated with cadmium (Cd)-laden soil (Ashraf et al. 2019). Additionally, two forms of cysteine-rich peptides, metal sulfides and chelate proteins, have been observed to play a significant role in pollutant detoxification. The process of detoxifying cadmium (Cd) concentration variation involves the participation of phytochelatin synthase, which acts as a Cd-binding peptide through carboxyl and sulfhydryl residues (Chai et al. 2013). Additionally, the detoxification process is facilitated by reactive oxygen species and antioxidant enzymes (Mahajan and Kaushal 2018). The presence of citric and oxalic acids in rhizobia has been observed to promote the availability of molecular pollutants and polycyclic aromatic hydrocarbons, which can increase the bioavailability of organic pollutants in plant roots (Fujita and Inui 2021; Yoshihara et al. 2014).

Plants possess various mechanisms that confer resistance to pollutants, including plasma membranes, antioxidant systems, cell chelation, and compartmentalization. Metallothioneins and phytochelatins play a key role in detoxifying contaminants such as copper (Cu). Recent studies have shown that phytochelatins are more efficient detoxifiers than metallothioneins, thereby preventing cellular damage (Liang et al. 2017; Ma et al. 2016a, b). In plants with high cadmium (Cd) accumulation levels, detoxification occurs through vesicle sequestration or cysteine-rich protein binding in which the Cd^{2+} is chelated into vesicles and removed from cell cytoplasmic lysates. The detoxification of pollutants within vesicles entails the utilization of a multitude of metabolites in the cytoplasm. This process is facilitated by exchange transporters and ATPase, which sequesters the pollutants in vesicles (Mahajan and Kaushal 2018). Additionally, plants can convert the pollutants they absorb into non-toxic and volatile compounds that are subsequently released into the environment. These mechanisms are commonly referred to as plant volatilization (Gavrilescu 2022).

Improving the efficiency of phytoremediation

Recent studies have demonstrated that incorporating support from plants, biochar, and microorganisms can significantly enhance the potential for plant restoration (Patra et al. 2020). However, it has been observed that pollutants can negatively impact plant functional ability when soil concentrations are high. Therefore, it is imperative to explore and implement solutions that complement phytoremediation, enhance remediation efficiency, and establish an ecological balance (Diaconu et al. 2020; Gavrilescu 2022; Khalid et al. 2021). Currently, some of the most promising approaches include microorganisms, chelating agents, biochar, and composting.

Microbiome

The optimization of plant repair efficiency is a multifaceted process that necessitates a combination of microbial and plant repair techniques. By synergizing their efforts, bacteria can enhance their operational capacity and mitigate plant stress from soil pollution (Gavrilescu 2022). Certain bacterial strains, such as *Pseudomonas aeruginosa*, *Escherichia*, and *Bacillus*, exhibit remarkable efficacy in addressing heavy metal contamination by secreting organic acids and polysaccharides that improve their solubility (Sharma 2021). In addition, the utilization of plant-growth-promoting bacteria has been shown to produce growth hormones that aid in the absorption of pollutants and enhance overall plant growth (Gavrilescu 2022; Ma et al. 2016a, b). Furthermore, the results of strain K1 and zinc oxide (ZnO) nanoparticles have been observed to be influenced by the presence of chromium (Cr) stress, which can alter wheat development and defense systems (Ahmad et al. 2022). In addition, various fungi (*mycorrhizae*) can significantly contribute to phytoremediation due to their extensive network of *mycorrhizal hyphae* that can penetrate small soil pores and enhance contamination uptake (Garcia-Sanchez et al. 2018). The *mycorrhizae* in clumps help to regulate the distribution of pollutants by inhibiting their transport from underground to the ground. Additionally, *mycorrhizae* increase the endurance of the plant for pollutants and push pollutants to the top of the plant (Gavrilescu 2022).

Current research into microbially assisted phytoremediation has been primarily focused on identifying effective hydrocarbon-degrading biosurfactants that can improve pollutant degradation. One promising candidate is *Ochrobactrum intermedium* CN3, which has been found to produce a highly efficient biological compound that can facilitate petroleum degradation. The dynamics of biomes have demonstrated remarkable tolerance to unfavorable conditions such as high temperatures and have been shown to produce a significant amount of oil sludge degradation in a relatively short period. These findings suggest that biosurfactants hold great potential as a future trend in developing biological solutions for repairing oil-polluted soils (Bezza et al. 2016; Lim et al. 2016). Plant phytoremediation efficiency is significantly influenced by inter-root activity and metal bioavailability. The chemical form of contaminants is closely related to their bioavailability. Plant growth-promoting *Rhizobacteria strains* can modify the properties and dynamics of contaminants in a trans-root environment by producing metabolic compounds, thus improving plant phytoremediation and phytostabilization efficiency (Manoj et al. 2020). In addition, root secretions such as organic acids, enzymes, and sugars would support microbial growth and enhance root area microbial activity. Moreover, root microorganisms can absorb plant nutrients or reduce plant oxidative stress to assist plants in degrading pollutants while interacting with plants (Harvey et al. 2002; Hoang et al. 2021).

The identification of appropriate mycorrhizal types is a critical aspect of phytoremediation in contaminated soil. The inoculation of host plants with ectomycorrhizal or tussock mycorrhizal fungi can enhance, reduce, or leave them unaffected by the accumulation of contaminants (Ma et al. 2014). The selection of appropriate mycorrhizal fungi promotes contaminant uptake in host plants and improves phytoremediation efficiency (Leudo et al. 2020; Shi et al. 2019). Furthermore, microorganisms that produce iron carriers or chelating agents play a significant role in bioremediation (Ashraf et al. 2019). For instance, the use of spores of *Bacillus megaterium* BM18-2 as a biofertilizer has been shown to improve the growth and contaminant tolerance of cadmium (Cd) hyperaccumulator hybrid *Pennisetum* (Kamal et al. 2021). Additionally, it has been observed that plants can have a beneficial impact on the microorganisms present in their environment. This is exemplified by the capability of mango grass to enhance the diversity of soil microbial populations (Bourgeois et al. 2015).

Chelating agents

The utilization of cheating agents has been investigated as a viable approach to remediate contaminated soils. Studies have demonstrated that chelating agents can effectively augment pollutant absorption at the plant roots, thus facilitating chelating-based phytoremediation methods (Bartoli et al. 2018). Additionally, non-super accumulators can also benefit from chelating agents to stimulate phytoextraction and enhance plant extraction (Patra et al. 2020). The interaction between chelates and pollutants plays a significant role in the translocation of pollutants across cells. This is primarily due to the formation of uncharged complexes, which alter the solubility of pollutants and enhance plant absorption (Gerhardt et al. 2017). For instance, due to its favorable complexation constant, ethylene diamine tetraacetic acid has been used to improve pollutant migration (Jiang et al. 2019; Yan et al. 2020). It was demonstrated that this acid can elevate copper (Cu) and cadmium (Cd) levels in alfalfa plants, making it a potent heavy metal chelator for plant extraction (Chen et al. 2022; Muhlbachova et al. 2012). Besides, ethylenediaminedisuccinic acid has also been shown to improve the bioavailability of pollutants such as copper (Cu), with a higher degree of bioavailability than the pollutants themselves (Song et al. 2016). Moreover, triacetic acid nitrate is a chelate that improves plant efficiency in extracting pollutants. This non-toxic substance degrades easily without polluting the soil, making it a safe option for extracting pollutants (Ashraf et al. 2019).

Genetic engineering

Genetic engineering techniques demonstrate considerable potential in reducing environmental toxins (Sharma 2021). Phytoremediation can be enhanced through genetic engineering to improve plant tolerance and accumulation. Studies indicate that genetically modified plants can stabilize and gather pollutants. Scientists have developed genes that facilitate the absorption of metals from the soil into the roots, the transfer of pollutants from roots to sprouts, and the introduction of chelating agents to explore analogous methods for organic contaminants (Gerhardt et al. 2017). Recent studies have shown promising results regarding genetic engineering to enhance plant resistance to pollutants. In particular, tobacco plants expressing TaVP1 which encodes wheat vacuolar H-pyrophosphatase, displayed increased vesicular storage. This increase contributed to the production of hydrogen (H) gradients and a driving force of pollutant transfer, resulting in a transgenic material that is more resistant to pollutants (Fasani et al. 2018; Khoudi et al. 2012). Additionally, the genetic modification of *Brassica napus* has led to a significant increase in cadmium resistance, with engineered plants exhibiting 16 times greater resistance than their non-modified ones (Muthusaravanan et al. 2018). These findings suggest that genetic engineering may hold potential for developing more resilient plants.

Nano-restoration

Studies have demonstrated that nano-phytoremediation represents a promising approach to contaminated soil remediation by harnessing the properties of nanotechnology and plant-based remediation (Alka et al. 2021). The incorporation of nanomaterials into plants has shown remarkable potential in providing numerous benefits, including enhanced purification, detoxification, and elimination of toxic pollutants. Recent studies have demonstrated that nano-silica can significantly improve lead (Pb) absorption by plant roots (Moameri and Khalaki 2019). Additionally, various nanoparticles have been found to facilitate plant growth and development while also promoting the conversion or direct reaction of harmful pollutants such as gold (Au) and magnesium (Mg) nanoparticles into less harmful forms. Notably, nanometer-scale zero-valent iron particles are highly effective at remediating heavy metals (Alka et al. 2021). These findings highlight the promising potential of combining nanomaterials with plants for tackling environmental pollutants with greater efficacy.

Nanomaterials can remediate soil and increase plant protein levels, which ultimately promotes the growth of beneficial microorganisms in the soil and root zone. This in turn enhances the capability of plants to absorb pollutants and improves soil fertility (Elkhatib et al. 2018). The incorporation of nanotechnology in soil remediation has brought about a significant shift in the management of biological solids, resulting in a more efficient and effective cleanup of pollutants. For instance, the use of carbonization in heavy metal pollution remediation can decrease organic solute production, allowing plants to grow normally (Chai et al. 2013; Wei et al. 2021). These findings highlight the potential of nanotechnology-based approaches in addressing diverse soil pollution challenges.

Biochar, composting, vermicomposting, foliar spray

At present, researchers have developed cost-effective techniques aimed at soil remediation. The utilization of water, biochar, and bagasse represents an excellent option for managing contaminated urban soil (Al Chami et al. 2015). Biochar, a carbon-rich material derived from plant materials, possesses distinct physicochemical properties that enhance pollutant adsorption and increase pollutant bioavailability (Paz-Ferreiro et al. 2014). Biochar is a highly effective remediation technique, particularly when combined with other methods (Liu et al. 2013). This is partly due to its ability to enhance the activity of microorganisms essential for optimal plant growth. Additionally, the high cation exchange capacity of biochar inhibits the growth of disease-causing microorganisms, thereby promoting a healthy environment for plant growth (Patra et al. 2020).

Composting has been widely recognized as a highly effective method for stabilizing soil contaminants. This process has been found to significantly reduce the bioavailability of pollutants, which in turn minimizes their uptake by plants. Furthermore, composting has been shown to effectively decrease the mobility of pollutants in soils, thereby serving as an effective pollutant modifier (Ferreyroa et al. 2019). Recent studies have demonstrated that compost made from woodchips and biosolids can be particularly effective in reducing the activity of pollutants in the soil while also improving soil nutrient content (Lebrun et al. 2020). Research has shown that the combination of biochar and compost can yield superior results when it comes to enhancing soil properties and promoting the growth of willow plants. Compared to amendments that employ iron sand, these agents can also elevate soil potassium levels and pH (Qin et al. 2021). Both biochar and compost have demonstrated efficacy in improving soil organic matter content and pH. Specifically, biochar has been found to mitigate enzyme activity, which can then be restored to normal levels with composting (Tang et al. 2020). Overall, the application of biochar, compost, or a combination of both can transform the physical and chemical properties of contaminated soil.

The existence of certain pores in soil may pose a challenge to the penetration of microorganisms which are vital for controlling pollutants. Earthworms, through their continuous "digging action," can expand the pore spaces, thereby enhancing the infiltration of microorganisms and consequent remediation of pollutants. Additionally, earthworms can assimilate toxic pollutants into their bodies to undergo transformation or degradation, subsequently leading to neutralization. These activities positively impact all facets of the soil ecosystem (Kuppusamy et al. 2017). The implementation of vermicomposting practices within smallholder farming systems in China presents a promising opportunity for improved sustainability outcomes (Sodango et al. 2018). The combination of bioremediation technologies has been shown to further enhance the remediation of polycyclic aromatic hydrocarbons by up to 50% (Huang et al. 2004; Kuppusamy et al. 2017). Detoxification agents applied to soil or plant leaf surfaces can also mitigate the toxic effects of pollutants, with foliar spraying offering a particularly effective means of promoting plant growth (Qin et al. 2021). For example, the sulfur application has improved plant lead (Pb) resistance (Xu et al. 2023). Moreover, the application of phosphorus can effectively enhance the arsenic (As) pollution remediation by *Isatis cappadocica* (Karimi and Souri 2015).

Combined repair technique

The use of phytoremediation in conjunction with other remediation techniques has demonstrated improved efficacy in remediating lead (Pb) contamination. This comprehensive remediation approach can address varying degrees of pollution and soil challenges by combining plant and microbial remediation with physical and chemical methods or solely physical and chemical methods (Zheng et al. 2022). This method can reduce overall remediation expenses and shorten remediation time while reducing the environmental impact of clean-up operations.

Conclusion

The urbanization process has had a consequential impact on ecosystem services, primarily due to changes in land usage. As a result, there is an urgent need to focus on urban soil safety, given the prevalence of environmental pollution. Considerable research has been conducted on soil pollution in urban areas, with the primary objective of finding cost-effective and environmentally sustainable remediation methods. After analyzing various remediation techniques employed locally and internationally, it has been determined that phytoremediation is the most efficacious method for soil remediation. The present review focuses on utilizing various plant species to remediate diverse soil pollutants and the mechanisms that underlie plant-mediated soil pollution remediation. It is worth noting that relying solely on plants for soil remediation can be time-consuming. It is imperative to integrate auxiliary measures such as microorganisms, chelating agents, and foliar sprays to enhance phytoremediation efficiency. Current advancements in genetic engineering, nanotechnology, composting, and vermicomposting are being actively pursued to identify more effective ways of supporting phytoremediation, with the ultimate goal of safeguarding our urban soil environment.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10311-023-01663-6.

Acknowledgements The authors would like to thank the Ministry of Higher Education, Malaysia, under the Fundamental Research Grant Scheme (FRGS) Phase 1/2022 for supporting this project (Reference No: FRGS/1/2022/TK08/UMT/01/1), Vot No: 59703). The manuscript is supported by the Program for Innovative Research Team (in Science and Technology) in the University of Henan Province (No. 21IRT-STHN020) and Central Plain Scholar Funding Project of Henan Province (No. 212101510005). The authors would like to thank Saveetha Institute of Medical and Technical Sciences for the facilities and support provided.

Author contributions YZ contributed to data curation, validation, writing—original draft, methodology, and writing—review & editing. HG contributed to methodology and writing—review & editing. HL contributed to methodology and writing—review & editing. SSL contributed to methodology, writing—review & editing, and supervision. CS contributed to writing—review & editing. MV contributed to writing—review & editing. HSN contributed to writing—review & editing. RKL contributed to writing–review & editing. WP contributed to funding acquisition, writing—review & editing, and supervision.

Funding The authors have not disclosed any funding.

Data availability Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no conflict of interest in this paper.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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