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THE SEARCH FOR POTENTIAL REMEDIATION STRATEGIES AND SUSTAINABLE ALTERNATIVES FOR SAFE USE OF US EPA SUPERFUND SITES

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Background: Environmental contamination from US EPA Superfund sites has long posed a serious threat to public health and environmental sustainability. Increased environmental risk in areas near US EPA Superfund sites is evidenced by studies that have found that these areas are characterized by higher levels of toxic substances in the soil and air. Addressing the hazards these sites pose requires thoughtful planning and creative approaches that balance environmental restoration with community development goals. Reclaiming abandoned industrial and mining sites is imperative because it is an opportunity to enhance public safety, restore ecosystems and support communities. **Objectives:** The study aims to identify the best biological remediation methods for contaminated sites, with a particular focus on the most common contaminants documented in the US EPA Superfund site database. The study also aims to develop potential strategies to improve the environmental safety of the US EPA Superfund site. **Methods:** The current study is based on peer-reviewed articles published in English over a 10-year period from January 2014 to December 2023 indexed in the abstract databases Scopus, Google Scholar and PubMed (NCBI). A combination of relevant keywords was used to search for sources. Publications selected for research review were not limited to any particular geographic location of US EPA Superfund sites or investigators. **Results:** The most frequently studied pollutants (in descending order of frequency of mention in scientific studies) were polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), heavy metals, polychlorinated dibenzo-p-dioxins and -furans (PCDD/Fs) etc. The largest number of publications aimed at restoring US EPA Superfund lands using biological methods occurred in the period 2016 – 2018, with bioremediation, biosparging and phytoremediation leading among the biological techniques used. A detailed analysis of the studies found showed that these results were consistent with each other, since it was the most frequently studied methods that were used to remove the pollutants in question. **Conclusion:** By equipping bioremediation approaches with essential components, this resource enables swift and effective responses to pollution incidents, minimizing potential adverse impacts on public health, waterways, and groundwater systems caused by industrial and human activities. Combining biological approaches with robust risk mitigation strategies can further enhance environmental protection and safeguard nearby populations. The provided concentrated information on various biological remediation practices, which are classified based on certain criteria, forms the basis of a strategy to improve environmental safety and implement sustainable alternatives for safe use of previously contaminated sites.

Keywords: environment; contaminants; remediation, risks; public health; ecosystems; polycyclic aromatic hydrocarbons (PAHs); polychlorinated biphenyls (PCBs); heavy metals.

INTRODUCTION

Environmental contamination from United States Environmental Protection Agency Superfund sites (US EPA Superfund sites) has long posed serious threats to public health and environmental sustainability, and has exposed companies to financial and legal problems (Mooney et al., 2025; Kiaghadi et al., 2021). Many older sites operated without modern environmental controls, leaving behind persistent contamination from petrochemical, construction, and industrial waste.

Exposure to hazardous substances from US EPA Superfund sites is often exacerbated by extreme weather events such as hurricanes, floods, and wildfires, which have become more frequent and unexpected in the past decade due to global warming (Kiaghadi et al., 2021). The researchers found that US EPA Superfund sites were associated with higher plasma PFOS, PFHxS, PFPeS and PFHpS (Li et al., 2025); higher levels of air toxicants (including PM 2.5) and reduced microbial biomass in soils were correlated with proximity to US EPA Superfund sites (Mooney et al., 2025; Akinwole et al., 2024), suggesting increased environmental risk in areas near these sites.

Sites such as abandoned mines, a particularly glaring example of industrial neglect, offer both challenges and opportunities. Historically left to their own devices and turned into hazardous wastelands, these sites have been successfully repurposed in several countries, including Australia, Canada, China, Romania, South Africa, the United Kingdom, and the United States, into community assets such as energy facilities, year-round agricultural areas, and even spaces for sports, science, and hospitality (Schneider & Greenberg, 2023). According to Tyson (2020), there are over one million abandoned mines worldwide, with over 500,000 in the United States alone. Addressing the hazards these sites pose requires thoughtful planning and creative approaches that balance environmental restoration with community development goals. Addressing the dangers these sites pose requires thoughtful planning and creative approaches that balance environmental restoration with community development goals. Programs like the United States Environmental Protection Agency's Superfund initiative have been pivotal in mitigating risks and restoring hazardous waste sites, though equitable solutions demand inclusive decision-making and attention to local needs. For indigenous communities in Canada and the United States, the stakes are particularly high. Many contaminated sites overlap with traditional lands, directly affecting cultural practices, food systems and health (Chong & Basu, 2023).

The development of potential strategies to improve environmental safety and implement sustainable alternatives for the safe use of previously contaminated sites is based on a study of the risks and environmental problems of areas close to US EPA Superfund sites. To address these environmental issues, integrating indigenous knowledge systems into remediation frameworks is critical which moves beyond generic risk assessments, fostering culturally relevant strategies that prioritize accountability and sustainability (Yan et al., 2020). Collaborative management informed by diverse stakeholder perspectives ensures fair outcomes and supports the transformation of contaminated sites into safe, productive spaces. Reclaiming abandoned industrial and mining sites is imperative because it is an opportunity to enhance public safety, restore ecosystems and support communities. By leveraging innovation, inclusive planning and cultural sensitivity, hazardous sites can be restored and serve as valuable assets for future generations.

A systematic review is one of the key research tools that is a thorough and rigorous analysis of available research and has become increasingly popular in recent years because it provides an objective and comprehensive picture of the state of knowledge, taking into account the available data. A systematic review contributes to informed decision-making in modern science because it can effectively cope with information noise, identify key knowledge and trends, and identify promising areas for further research. The purpose of a systematic review is to obtain an objective and comprehensive picture of the state of knowledge, taking into account the available data.

Therefore, the current review aims to examine existing biological control strategies for environmental contaminants at U.S. EPA Superfund sites. Accordingly, the study aims to provide answers to the following questions:

Question 1: What are the predominant environmental contaminants studied at US EPA Superfund sites and their associated risks to public health and ecosystems.

Question 2: What are the best biological practices for remediation of contaminated sites, with a particular focus on the most common contaminants documented in the US EPA Superfund sites Database.

Question 3: Suggest potential strategies to improve environmental safety and implement sustainable alternatives for safe use of previously contaminated sites.

Given that there is extensive research in the current field, a better understanding of these advances and existing gaps, as well as future research needs, requires a systematic review of research findings for sustainable development for future generations.

METHODOLOGY

The hallmarks of a systematic review are rigorous methodology, minimization of bias through the use of statistical methods, and the ability to analyse and synthesize large amounts of data. To ensure the quality and reliability of research results, systematic review methodology has evolved significantly in recent years, facilitating more transparent, complete, and accurate reporting of systematic reviews, thereby facilitating evidence-based decision making. PRISMA 2020 has been established as a robust methodology for original systematic reviews of studies (Higgins et al., 2019). The current study is based on peer-reviewed articles published in English over a 10-year period from January 2014 to December 2023. The inclusion and exclusion criteria for scientific papers were as follows.

1. The search for studies for the review was performed in three abstract databases: Scopus, Google Scholar, and PubMed (NCBI).

Scopus (by Elsevier) is the largest database of peer-reviewed literature abstracts and citations from various fields, with a total of 24,600 titles and 5,000 publishers. Scopus fully covers Web of Science, MEDLINE, EMBASE, and ScienceDirect (Nogueira et al., 2022; Arachchige et al., 2021), so these databases were not included in the source search to avoid multiple literature matches.

Google Scholar is one of the three (among Scopus and Web of Science) most important databases of scientific publications available for citation analysis. Google Scholar provides the ability to search by keywords, author, and article title. There is also an advanced search with additional features. It is a freely available search engine that indexes full text or metadata of scientific literature in various publication formats. This source contains more "grey literature" such as dissertations, books, manuals, conference proceedings, etc., which may be missed in another database.

PubMed (NCBI) database is an electronic search engine with free access to 30 million publications from 4800 indexed journals on medical topics. PubMed is suitable for scientific publications on narrow medical topics, while Scopus is more specialized in interdisciplinary studies. Thus, PubMed was chosen as an additional source that can provide important information for health risk analysis.

2. The combination of words used to search for sources. The keywords were entered in English in different variations: contaminants/pollutants AND superfund AND Biopiles/ Bioaugmentation/Biostimulation/Bioremediation/Biosparging/ Phytoremediation.

3. Evaluation of sources. The preliminary evaluation of sources was based on the title and abstract to determine that the source is relevant to the topic under study. Sometimes, for the convenience of scientists, the specified databases offer similar studies, i.e. studies that do not directly answer the specified query, but are as close as possible to the search topic. Since such well-developed databases as Scopus, Google Scholar and PubMed are equipped with "smart" algorithms, in most cases the suggested alternatives correspond to the search queries, and therefore, such publications were also taken into account.

Next, the publication hits identified were reviewed to exclude duplicates. Once duplicates were excluded, the remaining publications were critically reviewed, requiring papers that: (i) identify gaps in U.S. Environmental Protection Agency-mandated contaminants at US EPA Superfund sites and their associated risks to public health and ecosystems; (ii) examine biological remediation techniques for US EPA Superfund sites; (iii) only studies that provided specific numerical results and recommendations for at least one biological remediation technique for US EPA Superfund sites were considered; and (iv) publications selected for research review were not limited to any particular geographic location of US EPA Superfund sites or investigators.

All identified research results were reviewed and synthesized. In some cases, cross-referencing was considered if it was useful to the current study.

RESULTS

A literature search using keywords yielded a total of 5,750 scientific studies related to environmental contaminants and adverse effects of US EPA Superfund sites. In the first evaluation, 4,228 records were removed as duplicates – 355 documents as off-topic – 1,979, not published in English – 1,894. The remaining 1,522 papers were subjected to full-text

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evaluation for compliance with content-related criteria (provided scientific results). Some full texts (43 documents) were unavailable for various reasons, 14 papers had difficult writing style, and 118, 248, and 462 papers were rejected as not directly meeting stated criteria (i), (ii), and (iii), respectively (Figure 1).

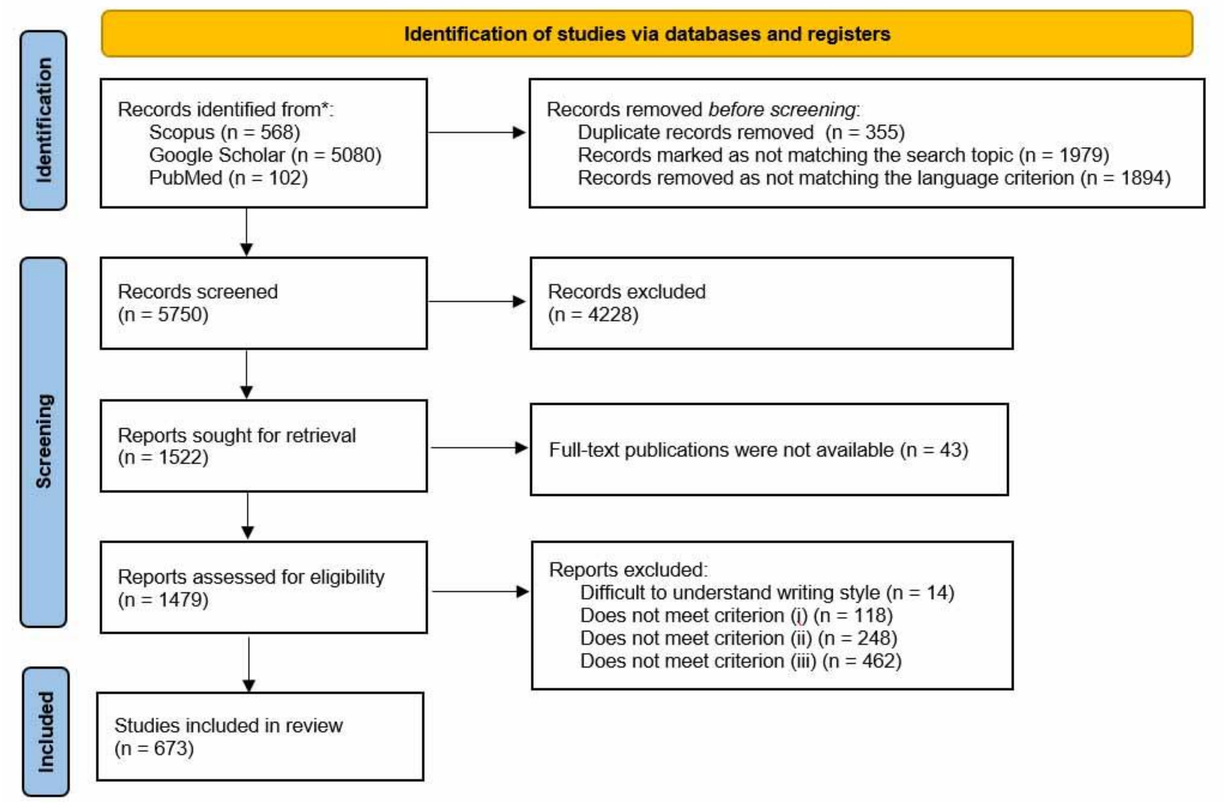

Figure 1. Systematic representation of inclusions and exclusions of scientific publications according to the search methodology

The following were the most frequently studied contaminants (in descending order of frequency of mention in scientific studies): polycyclic aromatic hydrocarbons (PAHs); polychlorinated biphenyls (PCBs); heavy metals such as arsenic, lead, chromium, manganese, nickel, barium, cobalt, zinc, cadmium, and mercury; polychlorinated dibenzo-p-dioxins and -furans (PCDD/Fs); and polyfluorinated substances (PFAS), dichlorodiphenyltrichloroethane (DDT), polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), and benzenes.

Exposure PAHs are genotoxic, carcinogenic, mutagenic in nature and as such, negatively impact humans, animals, aquatic life and plants by decreasing soil oxygen solubility and permeability; PAH-rich wastewater retards plant growth and increases plant toxicity (Zafra et al., 2015; Jain et al., 2020). In addition to acute and chronic health risks such as metabolic disorders, PAHs can cause cancer in various tissues including prostate, gonads and breast (Khanverdiluo et al., 2021). PAHs such as phenanthrene, naphthalene, anthracene, fluoranthene, pyrene, benzo(a)anthracene and benzo(a)pyrene can cause laryngeal and throat cancer. If the concentrations of PAHs increase through various exposure routes such as drinking, inhalation, etc., their total concentration may exceed the excess lifetime cancer risk standards set by the USEPA for carcinogenic chemicals, thereby adversely affecting human life. These substances have been documented to have very high levels of toxicity and may bioaccumulate, leading to subsequent biomagnification (Jain et al., 2020). The main source of these substances entering the human body is through food. According to FAO, the world consumption of cereals is about 147.1 kg/person/year, with consumption being particularly high in Europe, Africa and America. The most commonly consumed cereals are wheat, rice and maize, as well as products made from them. Grown on contaminated soils, these crops, and accordingly products from them, are contaminated with PAHs. Studies have found that fried wheat products have PAHs levels of 9.90 – 90.0 µg/kg, and in bread and cereals – 0.22 – 1.62 µg/kg (Einolghozati et al., 2022). Consumption of vegetation grown on contaminated lands and water by ruminants contributes to high PAHs content in milk. Exposure to high temperatures during cooking can lead to the combustion of organic materials and the formation of PAHs (Shoaei et al., 2023). PAHs pose a significant health risk to infants through the consumption of human milk. Like other food sources, human milk can be exposed to these toxic environmental pollutants. Some studies have found that human milk, due to its content of lipophilic tissue and various lipids, is susceptible to the accumulation of compounds with lipophilic nature, such as PAHs (Khanverdiluo et al., 2021).

Benzene is inherently carcinogenic and reduces the production of both red and white blood cells, which negatively affects the lymphatic system and central nervous system (Dehghani et al., 2018; Carvajal et al., 2018).

Researchers have detected over 600 chemicals at US EPA Superfund sites. The dominant heavy metals are lead at 43% of sites, trichloroethylene at 42%, chromium at 35%, and arsenic at 28% (Watts & Teel, 2014). For example, within the Tar Creek Superfund Site, a study of soil characteristics and concentrations of 20 metals found excess concentrations of Pb, Zn, Cd, and As. Many of the sampling sites include soils near agricultural fields, posing a direct threat to the population through consumption of contaminated crops, since over 90% of heavy metal exposure occurs through ingestion of contaminated food and to a lesser extent through dermal contact or inhalation

(Beattie et al., 2017; Calderon et al., 2023). Studies have documented that the following elements: cadmium, lead, nickel, mercury, arsenic, and copper are non-biodegradable and can bioaccumulate in living organisms, mainly in the liver and kidneys (Chen et al., 2021). Studies have shown that humans can absorb heavy metals through the consumption of contaminated foods, which contributes to decreased intellectual abilities, damage to the nervous system and heart disease, gastrointestinal problems and kidney disease, increased bone fragility and, as a result, fractures, and the development of cancer (Adam et al., 2022). Acute poisoning of the body occurs as a result of short-term exposure to relatively high doses of heavy metals, while chronic toxicity occurs as a result of consuming low concentrations of pollutants over decades. Excessive absorption of heavy metals from contaminated soils through agricultural crops reduces food safety and increases human health risks.

Studies on experimental animals have revealed a significant number of negative effects of dioxin exposure, namely: dysfunction of the immune and reproductive systems, disruption of the structure and/or function of the nervous system, endocrine disorders and tumour formation. At the same time, studies conducted with some people exposed to dioxins in the professional sphere or randomly demonstrate skin diseases and the occurrence of tumours, deterioration of the reproductive system such as a decrease in the number and weakness of spermatozoa and poor embryo development (Zheng et al., 2022a). When studying the serum PCDD/F levels of workers of the Escambia Wood Treating Company Superfund site and residents exposed to contamination from the plant, it was found that 23.4% of the subjects had diabetes, 68% were classified as hypertensive, 12.8% were diagnosed with cancer, which exceeded the national average for these diseases. Most of the subjects had serum PCDD/F levels higher than background levels. It has been documented that PCDD/F congeners have a wide range of half-lives in humans, which can be up to almost 20 years, which contributes to bioaccumulation over time for most of them (Karouna-Renier et al., 2007).

The number of academic publications on different biological remediation techniques for US EPA Superfund sites for each year from 2014 to 2023 is shown in Figure 2.

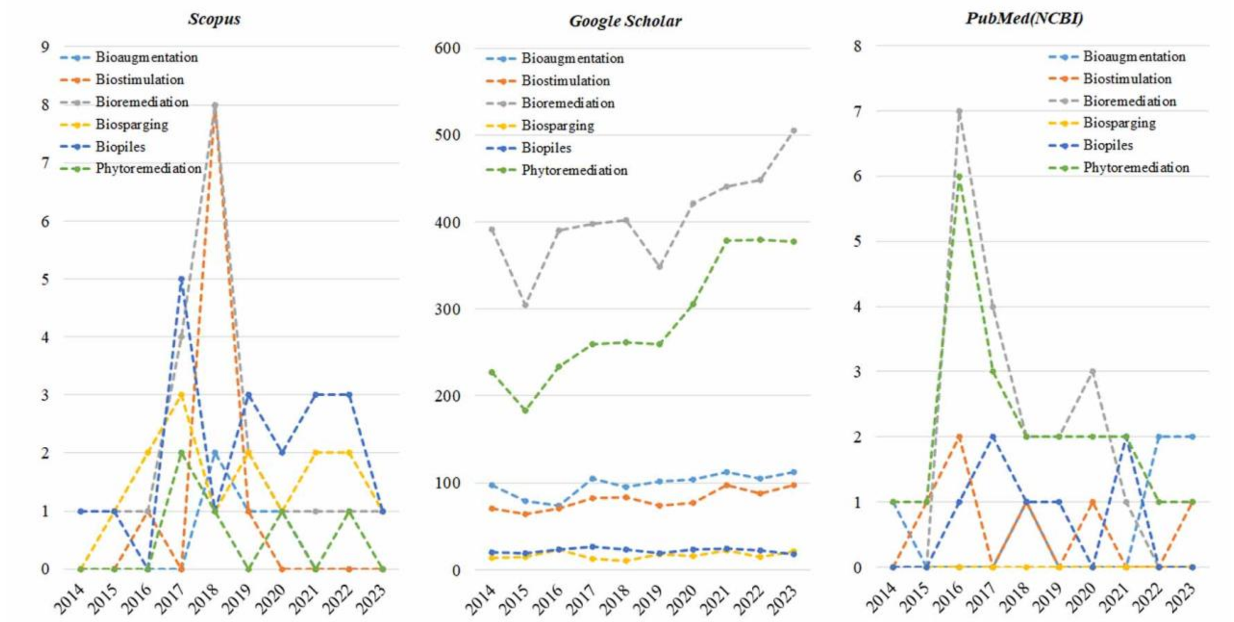

Figure 2. Number of academic publications in the period 2014–2023 on each pollution control technology (sources): a – Scopus; b – Google Scholar; c – PubMed (NCBI)

The largest number of publications aimed at restoring US EPA Superfund lands using biological methods occurred in the period 2016 – 2018, with bioremediation, biosparging and phytoremediation leading among the biological techniques used. However, an analysis was conducted of all the studies in the scientific publications found.

DISCUSSIONS

Remediation of environmental pollutants

Remediation aims to restore the functionality of soil, water or air after contamination, minimizing environmental and health risks (Zabbey et al., 2017). Success depends on the suitability of the chosen method to the specific circumstances and environment, taking into account factors such as contaminant type, level, location and regulatory requirements. Physicochemical methods, including chemical immobilization, extraction and oxidation, are expensive and invasive (Zabbey et al., 2017; Uguru & Udubra, 2021; Jiaming et al., 2021; Sánchez-Castro et al., 2023). Combined methods have demonstrated the best efficiency and shortest treatment time with low cost and the least impact on the environment (Michael-Igolima et al., 2022). They are followed by biological methods as the cheapest and most environmentally friendly for remediation purposes. Biological approaches such as microbial remediation and phytoremediation are gaining recognition as less intrusive and more environmentally friendly (Escobar-Alvarado et al., 2018), although they are slower.

Thus, some critics of microbial remediation are of the opinion that it takes more time and, for example, does not effectively remove oil from the soil at high concentrations. Other researchers report that increasing the efficiency of remediation and reducing the duration of treatment can be achieved by combining bioaugmentation and bio-stimulation (Michael-Igolima et al., 2022). The disadvantages of bioremediation include that the concentration of some pollutants will not be reduced to zero, although it will gradually decrease during treatment. This means that some residual amount of the pollutant will always remain, which is justified by the low level of the pollutant, which is unfavourable for supporting the continuation of biodegradation when the growth of the number of microbes and their activity is ineffective. And on the other hand, this is justified by the low level of bioavailability of the pollutant for transformation by microorganisms (Barbato & Reynolds, 2021). Since heavy metals and neutral hydrocarbons are widely distributed at US EPA Superfund sites and can persist for long periods of time, bioaccumulation may directly or indirectly threaten the environment and humans (Zhu et al., 2015; Sanga et al., 2023). Meanwhile, phytoremediation, as soil remediation among other contaminated soil remediation strategies, has attracted much attention due to its effectiveness and cost-effectiveness (Wu et al., 2021).

Table 1 presents remediation strategies for the fourteen major pollutants in the EPA database, but specific site conditions and regulatory restrictions may affect their implementation and success. A comprehensive site assessment and consultation with environmental experts is recommended before beginning a clean-up strategy.

Table 1. Recommended biological remediation techniques for top fourteen pollutants found at US EPA Superfund sites

Causes	Human health hazards	Environmental hazards	Ideal remedial strategy	Bioremediation and phytoremediation agents
Pollutant: Polycyclic Aromatic Hydrocarbons (PAHs)				
Dyes, plastics, pesticides, and medicine production	Cancer, developmental issues, immune system disorders	Contamination of soil, water, and air	Bioremediation: on-site land farming and composting, aerobic and anaerobic treatment	Various strains of bacteria and fungi (Biswas et al., 2015; Sayara & Sánchez-Castro et al., 2023; Ali et al., 2022; Thacharodi et al., 2023) Genetically engineered microorganisms (GEMs) (Wu et al., 2021)
Pollutant: Polychlorinated Biphenyls (PCBs)				
Electrical equipment, insulation	Skin disorders, liver damage, reproductive issues	Persistent in the environment, bioaccumulation in wildlife	Bioremediation	Various strains of bacteria and fungi, biochar (Wu et al., 2021; Valizadeh et al., 2021)
			Phytoremediation	*Brassica juncea*, *Avena sativa*, *Brachiaria decumbens* and *Medicago sativa* (Pino et al., 2019; Halfadji et al., 2022)
Pollutant: Arsenic (As)				
Pesticides, wood preservatives	Melanosis and skin cancer, cardiovascular and respiratory (disease) disorder, brain damage, muscle weakness, immuno-toxicity.	Soil and water contamination	Phytoremediation: phytovolatilization, phytostabilization, phytoextraction, phytofiltration, (Niazi et al., 2016; de Souza et al., 2019)	Pteris vittata, Water hyacinth (*Eichhornia crassipes*), Water Cabbage (*Pistia stratiotes*), Pteridaceae, *Ipomoea aquatica*, *Hydrilla verticillata*, *Lemna gibba*, *Lemna minor*, *Spirodela polyrhiza*, *Lepidium sativum*, *Azolla caroliniana*, *Azolla filiculoides*, *Azolla pinnata* (Yamamura & Amachi, 2014; de Souza et al., 2019; Sher & Rehman, 2019; Irshad et al., 2021; Anand et al., 2022; Donald et al., 2022)
Pollutant: Chromium (Cr)				
Metal plating, tanning industry	Respiratory issues, cancer, kidney and liver damage	Contamination of soil and water	Phytoremediation: phytostabilization, phytoextraction, (Ehsan et al., 2016; Yadav et al., 2018)	Certain plants, bacteria *Vinca rosea L.*, *Sorghum*, *Typha angustifolia L.*, *Hydrocotyle umbellata L.*, *Canna indica L.*, *Bambusa bambos* (Fernández et al., 2018; Taufikurahman et al., 2019; Bian et al., 2020; Ranieri et al., 2020; Pushkar et al., 2021)
Pollutant: Mercury				
Electrical devices, thermometers	Neurological damage, kidney problems, developmental issues	Bioaccumulation in food chains, water contamination	Bioremediation, Phytoremediation-phytovolatilization, phytoextraction (Marrugo-Negrete et al., 2015; Mahar et al., 2016)	Certain plants, bacteria *Klebsiella pneumoniae* M42, *Bacillus cereus*, *Bacillus thuringiensis PW-05*, *Eichhornia crassipes*, *Brassica juncea L. Czern*, *Jatropha curcas*, *Paspalum conjugatum L.*, *Cyperus kyllingia*, *Arabidopsis thaliana* plants (Muddarisna et al., 2013; Dash et al., 2014; Kumari et al., 2020; Raj et al., 2020)
Pollutant: Cadmium (Cd)				
Batteries, pigments	Kidney damage, respiratory issues, cancer	Contamination of soil, water, and air	Phytoremediation (Yan et al., 2020)	*Rhodobacter sphaeroides*, *Microcystis aeruginosa*, *Turnip landraces*, *Phytolacca Americana*, *Conocarpus Lancifolius* (Peng et al., 2018; Deng et al., 2020; Alou et al., 2022)

Pollutant: Lead (Pb)				
Batteries, pipes, paints	Neurological damage, developmental issues, cognitive impairments	Soil and water contamination	Phytoremediation: bioaugmented rhizoaccumulation, rhizofiltration, phytoextraction (Cheng et al., 2015; Azubuike et al., 2016; Jiang et al., 2019; Kaur et al., 2023; Pushkar et al., 2021)	*Conocarpus lancifolius*, *N. diderrichii*, *Medicago sativa*, *Helianthus annuus*, *Brassica juncea* (Yan et al., 2020; Aloud et al., 2022; Ojo & Sridhar, 2020; Sevak et al., 2021; Mitra et al., 2021)
Pollutant: Nickel (Ni)				
Stainless steel, batteries	Lung and nasal cancer, skin allergies, respiratory issues	Contamination of soil and water	Phytoremediation	General, *Microbacterium oxydans Strain CM3 and CM7*, *Bacillus thuringiensis*, *Bacillus altitudinis MT422188* (Minari et al., 2020; Heidari et al., 2020; Babar et al., 2021)
Pollutant: Manganese (Mn)				
Plumbing, electrical wiring	Gastrointestinal issues, liver damage, ecotoxicity	Contamination of soil and water	Phytoremediation	General, Papiliotrema huenov, Stenotrophomonas maltophilia PD2 (Ghosh & Saha, 2013; Cornu et al., 2017; Nguyen Van et al., 2021)
Pollutant: Polychlorinated dibenzo-p-dioxins and -furans (PCDD/Fs) and polyfluorinated substances (PFAS); Polychlorinated biphenyls (PCBs); Dichlorodiphenyltrichloroethane (DDT)				
Petroleum products, waste, combustion processes	Genotoxic, carcinogenic, mutagenic effects; metabolic disorders; prostate cancer, breast cancer, larynx cancer, throat cancer; bioaccumulation in living tissues	Pollution of air, soil and water: decrease in oxygen solubility in soil and its permeability; slowing down of plant growth, increase plants' toxicity	Microbial reductive dehalogenation/dechlorination (Nijenhuis & Kuntze, 2016; Zhang et al., 2022b)	The obligate organohalide-respiring *Dehalococcoides mccartyi strains* CBDB1, 195, DCBM5, reductively dechlorinate PCCDs to lower chlorinated dioxins (Pöritz et al., 2015; Adrian & Löffler, 2016)
			Bioaugmentation involving microbial consortia results in repeated and efficient purification (Nwankwegu et al., 2022)	Microbial diversities from exogenous sources (Nwankwegu et al., 2022)
Pollutant: BTEX				
Gasoline, vehicle exhaust gases, anthropogenic activities and biogenic resources, gas and oil production, pipeline explosions	Carcinogenic and non-carcinogenic harm to the population, respiratory problems, eye irritation, blood disorders, cancer and mutagenesis	Global warming, formation of tropospheric ozone, reduction in soil productivity	Biodegradation by local microbial consortium enhanced by bio-stimulants	Microbial communities supplemented with bios-timulants (Ali et al., 2023)
			Microbial bioremediation	*M. esteraromaticum*, *B. infantis* (Kaur et al., 2023)
Pollutant: Trichloroethylene (TCE)				
Industrial solvent, degreaser	Liver and kidney damage, respiratory issues, cancer	Contamination of soil, groundwater, and surface water	Bioremediation: bioaugmentation, biostimulation, biosparging, bioreactor, bioventing, biopilng (Underwood et al., 2022)	Various strains of bacteria: *Flavobacterium*, *Clostridium*, *Desulfotomaculum*, *Desulfuromonas*, *Nitrospira*, *Sphingomonas*, *Acidovorax*, *Bacillus*, *Pseudomonas*, *Alcaligenes denitrificans ssp. xylosoxidans JE75*, *Rhodococcus erythropolis JE77*; zero valent iron magnetic biochar; pyrite; *Pseudomonas putida* (Peng et al., 2018; Koner et al., 2022; Wu et al., 2021)
			Phytoremediation: phytovolatilisation	*Hybrid Poplar plant*, *Zea Mays*, *Vetiver grass* (Janngam et al., 2010; Moccia et al., 2017)

Pollutant: Tetrachloroethylene (PCE)				
Dry cleaning, metal degreasing	Liver and kidney damage, respiratory issues, cancer	Contamination of soil, groundwater, and surface water	Bioremediation: biostimulation, bioaugmentation, electrokinetic-enhanced bioremediation	Anaerobic/aerobic permeable reactive barrier, *Desulfitobacterium sp. strain Y51, Dehalococcoides ethenogenes, electrochemistry*, microbial consortia (Chang et al., 2018; Chang et al., 2017)
			Phytoremediation	*Helianthus annuus L.* (Hadiuzzaman, 2019)
Pollutant: Dichloroethane (DCE)				
Chemical production, degreasing	Respiratory issues, liver and kidney damage, cancer	Contamination of soil, groundwater, and surface water	Aided-bioremediation, anaerobic reductive dechlorination	Certain strains of bacteria (Ciampi et al., 2022)

Microbial remediation

Microbial remediation, or bioremediation, involves breaking down chemical contaminants using microorganisms like bacteria, fungi, algae, and protozoa (Clarkson & Abubakar, 2015). This process accelerates the natural biodegradation of pollutants by providing bacteria with nutrients and oxygen. In-situ treatment occurs on-site, reducing costs, time, and risks associated with handling contaminants (OPG, 2023). Ex-situ methods involve excavating and treating polluted materials off-site, which is more complex and time-consuming but prevents contamination spread (Lim et al., 2016). Bioremediation was pioneered in the 1940s and modernized by George M. Robinson in the 1960s, leading to its widespread adoption for cleaning up various spills globally (Zabbey et al., 2017; OPG, 2023). Successful applications include oil spills like Mega Borg, Exxon Valdez, and Apex, with significant reductions of petroleum hydrocarbons observed in short timeframes (Bovio et al., 2017; Laura, 2018). Bioremediation holds promise for effectively addressing hydrocarbon and organic contaminant remediation worldwide. Figure 3 shows techniques used in biological remediation.

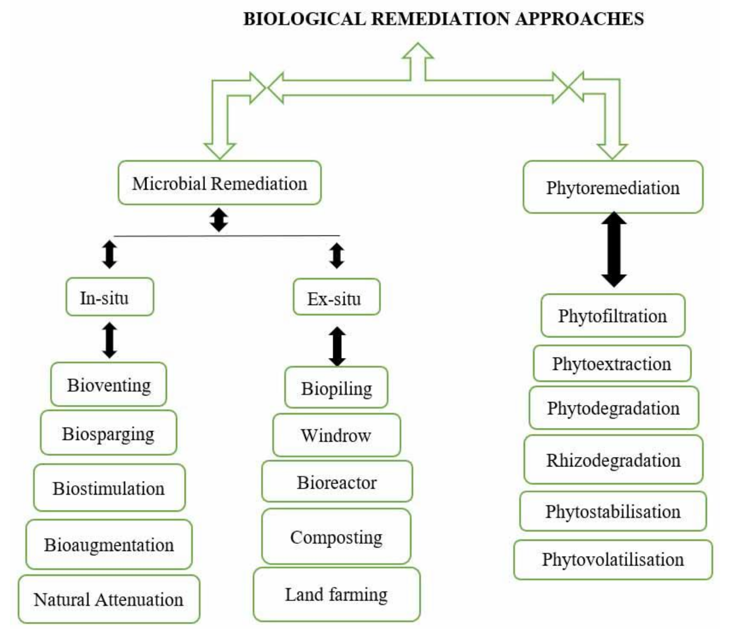

Figure 3. Bioremediation methods for the restoration of contaminated areas

Natural attenuation and bioremediation techniques

Natural attenuation, also known as natural remediation, is an in-situ strategy that leverages natural mechanisms to reduce the bulk toxicity, mobility, or volume of pollutants without human intervention (Maletić et al., 2019). Natural attenuation is generally a very slow process, which often results in poor environmental clean-up (Nwankwegu et al., 2022). At the same time, this approach is particularly effective for certain contaminants, as studies indicate that up to 25% of soil hydrocarbon pollutants can be successfully reduced using this technique (Koshlaf & Ball, 2017). Natural attenuation and its complementary bioremediation strategies offer environmentally friendly, cost-effective solutions for managing soil and groundwater contamination. Techniques such as bioaugmentation, biostimulation, biosparging, and bioventing work synergistically to accelerate pollutant degradation. Specifically, was studied natural attenuation, biostimulation and, bioaugmentation, in a comparative study of bioremediation of soil contaminated with diesel oil and reported the highest hydrocarbon degradation in both the light and heavy fractions at 72.7% and 75.2%, respectively of petroleum hydrocarbon (TPH) in the re-inoculated single strain-bioaugmentation system (Nwankwegu et al., 2022). Land farming, composting, biopiling, bioreactors, and windrow treatment further expand the toolkit for remediating diverse pollutants across varying environmental conditions. By understanding and optimizing these methods, their effectiveness and sustainability, can be enhanced, contributing to a cleaner and safer environment.

Bioaugmentation and bio-stimulation

Bioaugmentation involves introducing genetically modified or isolated microbial strains to break down contaminants more efficiently (Galitskaya et al., 2016). Research has demonstrated that *strain DCMB5* is a second *D. mccartyi* strain, in addition to *CBDB1*, with a particularly high capacity to respire halogenated aromatic compounds. The amazing ability of *strain DCMB5* to completely dehalogenate chlorinated dibenzo-p-dioxins expands the bioremediation potential of the *genus Dehalococcoides* (Pöritz et al., 2015). Genetically engineered microorganisms (GEMs) are good choices and efficient panaceas for safe and effective solutions to the bioremediation of polluted soils. However, given the insufficient ability of usual GEMs for combined contaminants in soil (e.g., heavy metals and PAHs), more efforts need to be paid out to construct multi-functional genetic engineering microorganisms (MFGEMs) that would be expected to improve the bioremediation of soil contaminated with heavy metals and PAHs (Wu et al., 2021).

In a study involving bioaugmentation using indigenous bacterial strains, namely *Acinetobacter radioresistens strain KA2*, which was isolated from oil waste sludge, the removal of petroleum hydrocarbons (TPHs) was demonstrated to be 67.64 – 89.56% over an eight-week composting incubation period (Nwankwegu et al., 2022). Evaluation of the effectiveness of microbial bioaugmentation and bio-stimulation demonstrated 97% TPHs removal in topsoil inoculated with the inoculum designated *MC2* in the study (Nwankwegu et al., 2022). Abena et al. (2019) recently evaluated the efficacy of bioaugmentation involving exogenous bacteria in the bioremediation of highly polluted sites and reported the removal efficiency of 48.10% under a half-life of 41.76 days. Bioaugmentation effectively improved both the rate and extent of PAH degradation in the consortium-amended system. The addition of 10% and 20% bacterial consortium suspensions resulted in the removal of 20.20% and 35.80% TPHs from the soil, respectively, after 8 weeks (Nwankwegu et al., 2022). In searching for mechanisms of BTEX recovery from contaminated sites, new strains were identified with respect to BTEX degradation, with the exception of *Bacillus subtilis*. The isolates, *Microbacterium esteraromaticum* and *Bacillus infantis* showed the highest degradation with 67.98 and 65.2% for benzene, 72.8 and 71.02% for toluene, 77.52 and 76.44% for ethylbenzene, and 74.58 and 74.04% for xylenes respectively (Kaur et al., 2023). Importantly, the study demonstrated that temperature is a positive stimulant for bioremediation, hence geothermal heating could also be a stimulant for in-situ bioremediation. Immobilizing hydrocarbon-degrading bacteria on carrier materials can enhance their density and competitive advantage (Zhang et al., 2019). However, this strategy is often unnecessary, as polluted soils typically develop resistant microbial populations over time (Volarić et al., 2021).

Based on the theoretical basis of anaerobic microbial reductive dehalogenation, Zhang et al. (2022b) identified two intrinsic relationships between microbial reductive dechlorination of PCDDs and electron density of chlorine substituents (ρCl). ρCl was found to be a reliable quantum chemical parameter for predicting dechlorination pathways and revealing dechlorination features (e.g., product toxicity, chlorine abstraction preference, complete and incomplete dechlorination, and their structural features).

Bioaugmentation often complements other techniques such as bioventing and biosparging to achieve better results. In contrast, bio-stimulation focuses on enhancing the degrading ability of native bacteria or other microbes by optimizing environmental parameters such as temperature, moisture, pH, and redox potential. This method also provides essential growth-limiting components like oxygen, vitamins, and substrates (Jiang et al., 2016; Galitskaya et al., 2016; Dindar et al., 2016).

Biosparging and bioventing

Biosparging involves injecting high-pressure air into contaminated groundwater or soil to enhance biological air sparging. This increases oxygen concentration, promoting microbial activity for contaminant removal. Compared to traditional excavation or pump-and-filter methods, biosparging is more cost-effective and efficient. It directly targets the saturated zone, yielding significant biodegradation results (Kao et al., 2008). Similarly, bioventing accelerates biodegradation by introducing air into the unsaturated zone, aiding the migration of volatile organic molecules (Sharma, 2020). Bioventing enhances pollutant degradation rates by injecting air and nutrients into polluted soils, stimulating native oleophilic bacteria to degrade petroleum hydrocarbons. Research shows an 85% degradation efficiency after 60 days, significantly outperforming natural attenuation's 64% (Macaulay & Rees, 2014; Thomé et al., 2014).

Land farming and composting

Land farming, also known as land treatment, involves spreading and tilling contaminated soil to promote aerobic microbial activity. This approach, combined with added moisture, minerals, and nutrients, effectively reduces petroleum product concentrations in soil (Kumar et al., 2018). Land farming is an environmentally friendly, cost-effective method that minimizes energy consumption while remediating polluted soil. Composting, on the other hand, combines contaminated soil with organic waste to provide nutrients for microorganisms. This ex-situ bioremediation technique supports bacterial growth, particularly thermophiles, in a high-temperature, nutrient-rich environment (Zouboulis et al., 2011). Composting sustainably enriches soil nutrients and transforms organic pollutants into less harmful forms (Dhaliwal et al., 2020).

Biopiling, bioreactors and windrows

Biopiling involves stacking contaminated materials to facilitate airflow and enhance natural remediation through oxygenation. This method integrates aeration and fertilization to boost microbial metabolic processes, creating optimal conditions for native microorganisms. Leachate collection bed systems further control biodegradation conditions, making biopiling effective in remediating various pollutants even in harsh environments (Rajendran et al., 2022; Gogoi et al., 2021; Gomez & Sartaj, 2014). Incorporating heating systems can accelerate the biodegradation process, reducing remediation times. Bioreactors represent the most advanced form of ex-situ remediation. These engineered systems precisely control environmental parameters to maximize microbial degradation of contaminants (Sharma, 2020). Bioreactors ensure consistent conditions for optimal biodegradation, offering a highly efficient approach to pollution remediation. Windrow treatment, another ex-situ technique, involves regularly turning heaped contaminated soil to promote native hydrocarbonoclastic bacterial growth. These bacteria degrade hydrocarbons through assimilation, biotransformation, and mineralization. Regular turning ensures uniform distribution of contaminants, nutrients, and microbial activity, yielding higher hydrocarbon removal efficiency compared to biopiling (Coulon et al., 2010). However, reduced aeration can lead to methane production due to anaerobic zones forming inside the heaps (Hobson et al., 2005).

Phytoremediation mechanisms

Environmental, 2020). contamination pose significant global challenges, with far-reaching socio-economic and public health implications. Globally, remediation of polluted environment, using eco-friendly materials has become a major concern (Uguru et al., 2022). Traditional physicochemical remediation techniques, while effective, are often costly and risk transferring contaminants to other environmental media. In contrast, phytoremediation offers an eco-friendly alternative by utilizing hyper-accumulating plants and their symbiotic microbes to break down, immobilize, or neutralize pollutants. Through mechanisms such as phytostabilization, phytodegradation, and phyto-extraction, this approach addresses chemical spills, including emerging organic pollutants, in a sustainable manner. Furthermore, phytomining allows for the recovery of valuable metals following remediation (Sharma, 2020).

One notable phytoremediation technique is phytovolatilization, in which plants absorb toxins from the soil, transform them into less harmful volatile forms, and release them into the atmosphere via transpiration (Yan et al., 2020; Abdullah et al., 2020). This method is particularly effective in detoxifying organic pollutants and certain heavy metals such as selenium, mercury and arsenic (Mahar et al., 2016; Naeem et al., 2020). For instance, *Brassica juncea* has demonstrated the capacity to efficiently volatilize Se (Yan et al., 2020). Unlike other phytoremediation techniques, phytovolatilization does not necessitate the removal of plant material; however, residual pollutants may persist in the environment, and volatilized toxins can be re-deposited into the soil by rainfall (Vangronsveld et al., 2009).

Another approach, phytostabilization, relies on plant roots to absorb, precipitate, and stabilize pollutants, thereby reducing their bioavailability and preventing their migration into other environmental systems (Yao et al., 2012; USEPA, 2000). Certain plant species contribute by producing chelating chemicals that stabilize contaminants in areas such as mining sites and waste management facilities (Eskander & Saleh, 2017; Saha et al., 2017). These plants immobilize pollutants, limiting their uptake and mobility in soil, and are thus instrumental in fostering vegetation regeneration in polluted regions (Yadav et al., 2018).

In the rhizodegradation process, also known as phyto-stimulation, soil bacteria in the rhizosphere stimulated by root microbial activity break down organic contaminants (Echereme et al., 2018; Abdullah et al., 2020). This process can occur naturally or be enhanced through the introduction of specific bacteria to optimize microbial conditions. While slower than phytodegradation, rhizodegradation enhances pollutant breakdown through the activity of bacteria, fungi, and yeasts associated with plant roots (Ali et al., 2013; Liao et al., 2016; Khalid et al., 2017; Al-Baldawi et al., 2017; Robichaud et al., 2019; Fahid et al., 2020).

Phytodegradation, on the other hand, involves the enzymatic breakdown of pollutants by plants and microorganisms in the root zone (USEPA, 2000). Plant roots release enzymes like dehalogenase and laccase, which expedite the degradation of contaminants (Lim et al., 2016). This method is effective against various organic pollutants, including TCE, BTEX, and PCBs (Gerhardt et al., 2009). Moreover, these plant-produced enzymes enhance rhizosphere bacteria activity, further aiding in contaminant oxidation.

The process of phytoextraction, or phytoaccumulation, employs plants to absorb and store pollutants from contaminated soil or water (Yao et al., 2012; Lim et al., 2016). This technique is especially effective for remediating environments contaminated with metals and organic compounds (Sarwar et al., 2017). Plants such as *Thlaspi caerulescens* and *Alyssum bertolonii* are notable for their ability to accumulate pollutants like copper, arsenic, nickel, zinc, and cadmium (Van der Ent et al., 2013; Reeves et al., 2018). Once pollutants are absorbed, the plants may need to be harvested and disposed of properly to prevent secondary contamination.

A related technique, rhizofiltration, involves cultivating plants in greenhouses with roots submerged in water. These plants, initially grown hydroponically in clean water, develop extensive root systems before being transferred to contaminated sites to absorb heavy metals. Once pollutants are accumulated, the plants are removed and disposed of. This method is particularly effective in altering the rhizosphere's pH to precipitate heavy metals onto the roots, thus preventing their flow into groundwater (Javed et al., 2019). Ideal rhizofiltration plants are characterized by high biomass, extensive root systems, and resistance to heavy metals. Both aquatic and terrestrial plants can be utilized; for instance, aquatic plants like duckweed and water hyacinth are preferred for wetland remediation, while terrestrial plants such as Indian mustard and sunflower are effective at adsorbing heavy metals (Rezania et al., 2016; Dhanwal et al., 2017).

CONCLUSION

This work categorizes various remediation methods based on specific criteria, providing a comprehensive guide for addressing serious environmental contamination at Superfund sites. The table presented serves as a proactive tool for preparing pollutant cleanup strategies, particularly for those actively handling noxious substances. By equipping remediation approaches with essential components, this resource enables swift and effective responses to pollution incidents, minimizing potential adverse impacts on public health, waterways, and groundwater systems caused by industrial and human activities. Focusing on the top chemical contaminants identified at US EPA Superfund sites, the outlined methods emphasize the importance of biological remediation techniques, which offer sustainable solutions to ensure that contamination need not be permanent. However, the need for stringent standards in the transport, storage, and handling of hazardous materials remains critical. Combining biological approaches with robust risk mitigation strategies can further enhance environmental protection and safeguard nearby populations, providing a valuable framework for remediation professionals addressing current and future contaminated sites.

Author's statements

Contributions

Conceptualization: M.H., A.N.D.; Data curation: M.H., A.N.D., B.L.S.; Formal Analysis: M.H., A.N.D.; Investigation: A.N.D., M.H.; Methodology: A.N.D., M.H.; Project administration: A.N.D., M.H.; Resources: M.H., A.N.D., B.L.S.; Supervision: A.N.D.; Validation: M.H., A.N.D., B.L.S.; Visualization: A.N.D.; Writing – original draft: M.H., A.N.D., B.L.S.; Writing – review & editing: M.H., A.N.D., B.L.S.

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