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Environmental Remediation Techniques for Contaminated Sites

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Abstract: This review article comprehensively overviews the various remediation techniques available for contaminated sites. Contaminated sites pose a significant risk to the environment and human health, and it is essential to remediate these sites to minimize the potential harm caused by pollutants. The article covers various remediation techniques, including physical, chemical, and biological methods. Overall, this review article is a valuable reference for anyone interested in understanding the current state of knowledge in remediation technologies for contaminated sites.

Index Terms: Contaminated sites, Groundwater cleanup, Remediation technologies, Soil remediation

1 Introduction

Accidents, spills during transportation, leaks from waste disposal or storage sites, or releases from industrial facilities how examples of ways that pollutants can enter the environment directly [1]. The public is constantly concerned about contaminated sites because of their potential harm to humans, other living things, the environment, and even property values. The environment and public health may be seriously in danger if the pollution problem is not discovered correctly, acknowledged, defined, researched, and realistically resolved. Also, it might harm the site's development and present or future land uses. The subdivision, development, and redevelopment of land; any change in land use, such as from commercial to residential; or from one type of commercial to another, such as from service station to office; where additions or alterations may be proposed to the existing landscape or infrastructure; and the transactions of land and properties should therefore be carefully considered [2].

The environment may occasionally be contaminated or polluted with hazardous materials during various operations across numerous industries. The organizations in charge of these situations must address the contamination. Examples of some accidents:

- 2006 Ivory Coast toxic waste dump

On the night of August 19, 2006, 12 trucks departed the port at Abidjan, Ivory Coast. The international company Trafigura had created toxic waste, which was placed on the trucks. The dangerous materials were dropped at 18 locations throughout the city, close to densely populated regions, during the night and early morning. The harmful consequences of the waste for nearby residents started to manifest almost immediately. The estimated number of deaths from this environmental crime was 15, and 108,000 people sought medical attention. Residents of Abidjan still have medical issues linked to chemical poisoning today.

Fig. 1. Showed the Ivory Coast toxic waste dump.

Fig. 1. Ivory Coast toxic waste dump [3].

- Love Canal Disaster, U.S.

Nearly 22,000 tons of chemical waste (polychlorinated biphenyls, dioxin, and pesticides) produced by the Hooker Chemicals and Plastics Corporation in the 1940s and 1950s were dumped there after a canal had been there before it was abandoned. This waste was initially located in the Love Canal area. The business later filled in and donated the property to Niagara Falls, which allowed for the construction of homes there. State investigators did discover a leak of dangerous substances into local homes' basements in 1978, though. Fig. 2 shows the love canal before and after the disaster.

During investigations, it was found that residents of the region had an abnormally high rate of chromosomal damage, which was probably brought on by prolonged exposure to toxic chemical wastes. Following a significant portion of Love Canal's evacuation, the state of New York bought the abandoned site. The structures close to the canal were demolished and covered with fencing. A $20 million settlement of claims against the Occidental Chemical Corporation, which had taken over Hooker in the late 1960s. The city of Niagara Falls was reached after protracted litigation between 1,300 former inhabitants of Love Canal.

Early in the 1990s, New York State stopped its cleanup efforts and deemed some areas of the Love Canal area safe for habitation. The region north of the landfill was given the new name Black Creek Village, and the state started selling homes there. Occidental agreed to pay New York $98 million in 1994 as compensation for the state's assistance in the Love Canal cleanup [4].

Fig. 2. Love canal before and after [5].

- The Toxic Truth

The story begins horrifyingly for the protagonists, the residents of Abidjan, Côte d'Ivoire, and ends tragically. They discovered poisonous trash had been deposited in several locations throughout their city on August 20, 2006, when they woke up. The symptoms of tens of thousands of victims included nausea, headaches, trouble breathing, stinging eyes, and scorching skin. Official records show that more than 100,000 people received treatment, although it is likely that the actual number of afflicted individuals was higher because of the records' limitations. According to the police report, up to 17 people died. Many people's worries persisted when the symptoms subsided with medical intervention and time. They have no idea what was in the trash six years later. It had been taken to Abidjan, exported from Europe, and dumped there, violating the law. Several domestic and foreign laws have been broken [6]. Fig. 3 shows the Toxic Truth.

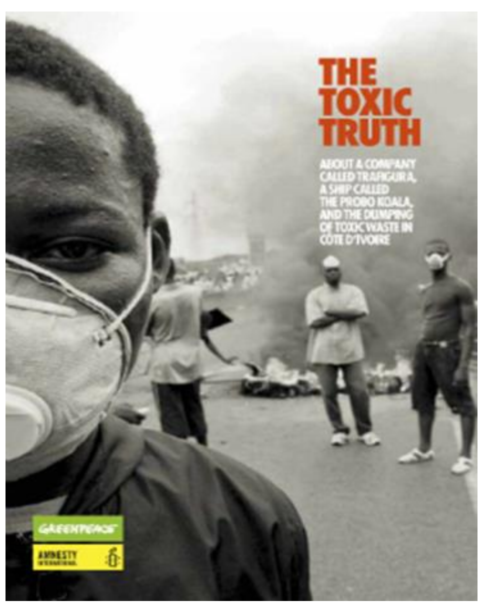

Fig. 3. The Toxic Truth [6].

- Minamata Disaster

The formal discovery of Minamata disease occurred on May 1, 1956, when a doctor in Japan described an "epidemic of an unknown ailment of the central nervous system." A nearby facility producing the chemical acetaldehyde (Chisso Corporation's chemical waste pipe) poisoned Minamata Bay, Japan, with mercury in the late 1950s. The mercury was bio-transformed into methylmercury, or organic mercury, by bacteria in the water, which then bioaccumulated and biomagnified in the fish muscle. Local cats that consumed the fish first started to stumble and die. The local population that relied on fish was mainly impacted by growing fetuses and young children. More than 2,000 individuals died, and countless others suffered life-altering injuries. They discovered that dilution is not the answer to pollution since the mercury discharged into the water was concentrated and had fatal repercussions when it came back. They also observed that the placenta does not act as a defense against environmental pollutants and that the fetus is highly vulnerable to mercury. A fungicide based on mercury was used to treat seed grain in Iraq during the 1970s, and unfortunately, people there once again learned these lessons [7]. Fig. 4. shows how people were affected by the Minamata disaster.

Fig. 4. How people were affected by the Minamata disaster [8]

The green economy places a strong emphasis on environmental cleanup. Whether polluted through years of industrial activity or by inadvertent releases, bodies and land areas of water must be remediated to restore them to their natural state or make them suitable for redevelopment. Removing contaminants or pollutants from soil, water, and other media is crucial in environmental remediation. Decreasing the number of dangerous pollutants promotes environmental and public health protection [9]. Brownfield sites are repaired through remediation, either for redevelopment or to return them to their original state. Cleaning up after hazardous waste disposal sites can be particularly difficult. Remediation projects can range from primary, expensive projects that require much work to clean up contaminated sites to smaller, less costly tasks, like cleaning up an oil spill on a highway. Sometimes a location is so toxic that all that can be done to keep it separate from the surrounding area is to fence it off. Most remediation projects start with a site evaluation to identify how much the project will cost and which technology would be best for the specific location [10].

Environmental media, such as sediment, soil, surface water, and groundwater, are all subject to environmental remediation. In contrast to soil remediation, which only involves topsoil, subsoil, and sediment, water remediation also involves groundwater and surface water. Depending on the severity and nature of the contamination, soil and water cleanup may be carried out separately or together [11].

2 Ex-Situ vs. In-Situ Remediation

Remediation technologies are varied but can also be categorized into ex-situ and in-situ methods. Ex-situ remediation involves physically transferring media from a contaminated site to another area for treatment, whereas in-situ remediation treats toxins where they are. The soil is removed if the contaminant is only present in the soil at an ex-situ site. If contamination has reached the groundwater, it is pumped out, removing the contaminated soil and water. Ex situ and in situ procedures both have advantages and disadvantages. In-situ treatments have a significant advantage: contaminated soil does not need to be removed or transported. The burden of in-situ treatments is that they are less effective than ex-situ remedial methods for removing contaminants. Also, excavation is expensive and exposes workers to health risks from contaminants; in-situ remediation procedures are preferred over ex-situ ones. Despite the high expense, ex-situ treatment typically delivers more consistent results, is easier to monitor, and takes less time to achieve efficient contamination cleaning. Decontaminated soils may be used for landscaping after ex-situ treatment [12].

3 Ex-Situ Remedial Options

- Dig-and-Dump (Landfills and Engineered Landfills)

The most common and traditional ex-situ cleanup technique is dig-and-dump. Dig-and-dump or excavation-and-disposal typically focuses on "hot spots," where toxins at a polluted site exceed established risk standards and necessitate cleanup. The dig-and-dump method, contaminated soils are removed and taken to landfills or other suitable disposal sites. Polluted soil must frequently be transported to secure landfills. An adequately designed area designated as a "landfill" for waste disposal is protected. With an expected annual disposal rate of between 5,000 and 230,000 t of waste per year, landfill types are relatively diverse and include inert waste landfills, solid waste landfills, and hazardous waste dumps. A secure landfill typically consists of four essential components: a bottom liner, a cover or "cap," a leachate collection system, and a natural hydrogeological setting. The bottom liners are layered on a dip in the ground shaped like a bathtub and are made of plastic, clay, or a combination. They are intended to stop waste from leaking into the environment. Leachates are prevented by covering or capping the landfill, supplemented with a system of pipes (a "leachate system") that collects the leachate. Any pumped leachate is handled at a waste treatment facility [13]. The 'bioreactor landfill' is a sanitary landfill location designed to transform and stabilize toxins via microbial processes within the first 5-8 years of bioreactor operation. It is an upgraded form of engineered landfill. The ability of bioreactor landfills to (a) reduce greenhouse gas emissions into the environment; (b) produce end products that do not require landfilling; (c) steeply decrease the cost of landfilling; (d) decrease the cost of leachate treatment, (capital and operating costs); and (e) reduce contaminant concentrations during landfill operation are some of the advantages of these facilities [12]. Fig. 5 shows the Excavation and Landfill Disposal Process Flow.

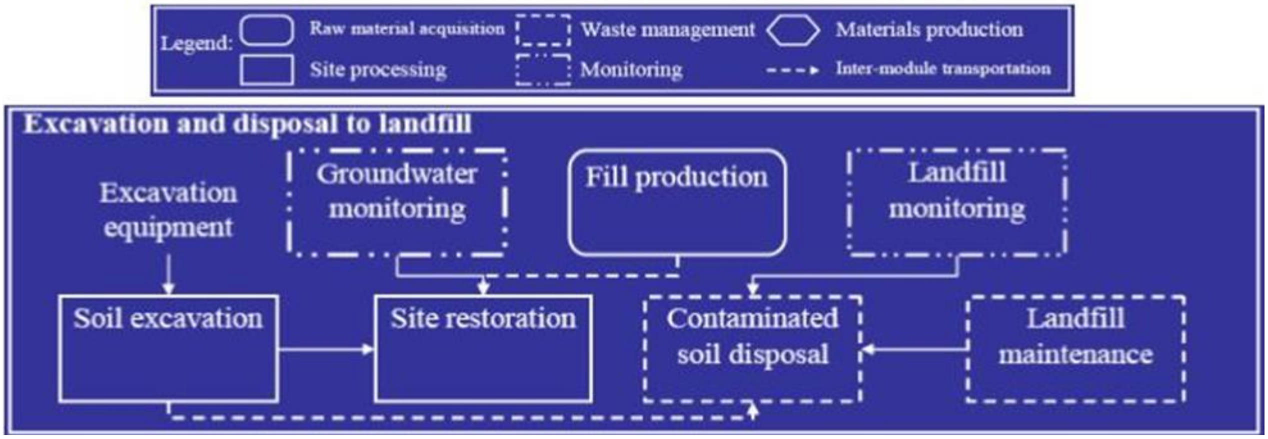

Fig. 5. Excavation and Landfill Disposal Process Flow

- Pump-and-Treat

Pump and treat removes contaminated groundwater from the ground, cleans it, and reintroduces it. Water is brought to the surface by a vacuum pump, where it is treated using various methods depending on the degree of contamination.

Water can be treated with activated carbon, which binds with chemicals in a solid form and enables them to be separated from the water, for example, if the water is contaminated with petroleum products. Water can also be run through various filters to remove specific contaminants or be treated with biological agents. Air stripping, which separates and removes specific contaminants by vaporizing and sucking them into an airstream, is another method for cleaning polluted groundwater [1].

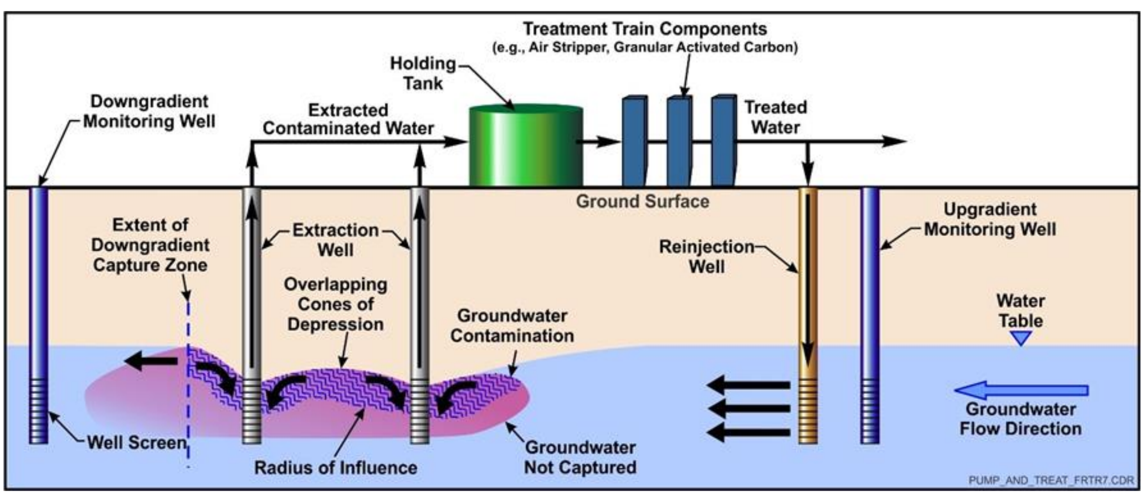

Fig. 6. Groundwater pump and treat process [15].

The pump-and-treat method often takes between 50 and 100 years to attain corrective goals; in most cases, such goals are never achieved. As a result of treatment, it becomes difficult to dispose of pollutants that have attached themselves to activated carbon. These limitations have led to the developing of alternatives to conventional pump-and-treat systems, including surfactant-enhanced remediation, metallic iron technology, permeable reactive barriers, etc. [16]. The traditional pump-and-treat system is no longer functional and has been modified to incorporate recently developed technology (nano or surfactant treatments, reactive barriers, etc.) [12].

- Incineration

Over the past 20 years, incineration technologies have become more significant as pump-and-treat methods have lost favor in treating environmental wastes. The process by which hazardous wastes are treated at extremely high temperatures (750–1200 °C) to impact their disposal is known by various names, including incineration, burning, and thermal oxidation. Different experimental units are used for incineration, including infrared combustors, which use silicon carbide rods powered by electricity to heat organic waste up to temperatures of 1010 °C, fluidized beds, which use high-velocity air with infrared as a heat source, and circulating bed combustors, which use high-velocity air to entrain moving solids and create a high-temperature flame to burn harmful hydrocarbons [17].

Incineration is expensive in terms of the upfront capital expenses to build a facility and the ongoing operating costs. While routine waste management problems necessitate practical repairs, incinerator equipment requires maintenance and is generally unreliable. Supplemental fuels are frequently needed to reach desired combustion temperatures, which might be expensive [12].

- Adsorption

Adsorption is the most popular, quickest, and least expensive technology for treating groundwater, industrial wastewater, air emissions, chemical spills, and removing various toxic substances. These substances include BTEX, ethylbenzene, xylene, trichloroethene, dichloroethane, PCBs, pesticides, herbicides, explosives, and anions like perchlorate and heavy metals. The most popular adsorbent, activated carbon, has been extensively used for water and air treatment, followed by activated alumina, sorption clays, synthetic ion-exchange resins, and forage sponge (an open-celled cellulose sponge with an amine-containing chelating polymer that selectively adsorbs toxic transition heavy metals) [12,18].

- Ion-Exchange

Ion exchange is the term used to describe the exchange of cations or anions between contaminants and the media. Resins typically comprise ion-exchangeable compounds (natural polymers with various ionic functional groups to attach exchangeable ions) [18]. The metallic ions are retained in the resins after the exchange of ions between the resin's cations and anions and the contaminated substances that occur when liquids are passed over a resin bed. When their capacity has been used up, resins can be regenerated for further use; occasionally, the resins are only designed for a single application. Both cationic and anionic resins have so far been utilized [19].

4 In-Situ Remedial Options

In-situ technologies include solidification and stabilization, soil vapor extraction, permeable reactive barriers, monitored natural attenuation, bioremediation and phytoremediation, chemical oxidation, steam-enhanced extraction, and in situ thermal desorption.

- Solidification and stabilization

Adding substances to a site during solidification causes those pollutants to bind together. While this doesn't remove the toxins from the environment, it does stop them from getting into more groundwater or spreading out over a larger area. As an illustration, a remediation project would combine contaminated soil with cement to create a solid block containing pollutants and prevent contamination from spreading through rain [20].

Chemically reactive substances are used for stabilization. By bonding with contaminants and stopping their spread, these substances change the contaminant's chemical composition, making it less dangerous or simpler to control or remove. Stabilization is frequently used in sites contaminated with heavy metals like arsenic and mercury [21].

- Soil vapor extraction

Enhanced volatilization, in situ volatilization, soil venting, and soil vapor extraction are other names for the in-situ soil vapor extraction method. Using extraction wells, a suction is delivered to the contaminated soil matrix to separate the toxins from the soil. SVE is a cleanup technique frequently used to remove volatile and some semi-volatile organic compounds (VOCs and SVOCs) in vapor form from the contaminated property. It is used to draw pollutants in vapor form out of contaminated soil. Many procedures can be used to regulate how much VOC and SVOC are removed by SVE. Advection, volatilization, desorption, and diffusion are examples of transport and removal mechanisms. SVE benefits from the contaminant's feature of volatility. Until the vapor pressure achieves equilibrium with the liquid, VOCs in the soil will quickly evaporate. The vapors can migrate through the soil alongside the natural atmospheric gases and fill the gaps between the soil grains. Any volatile liquid in the soil will evaporate if left in place for sufficient time, just like water in an open container. Yet, the process can take years or even centuries because of how slowly natural soil gas moves. The subsurface permeability will also significantly influence the time needed for this procedure. Soil structure, soil moisture, and groundwater depth affect how well soil vapor extraction works [22]. Fig. 7 shows the Typical soil vapor extraction (SVE) site and system.

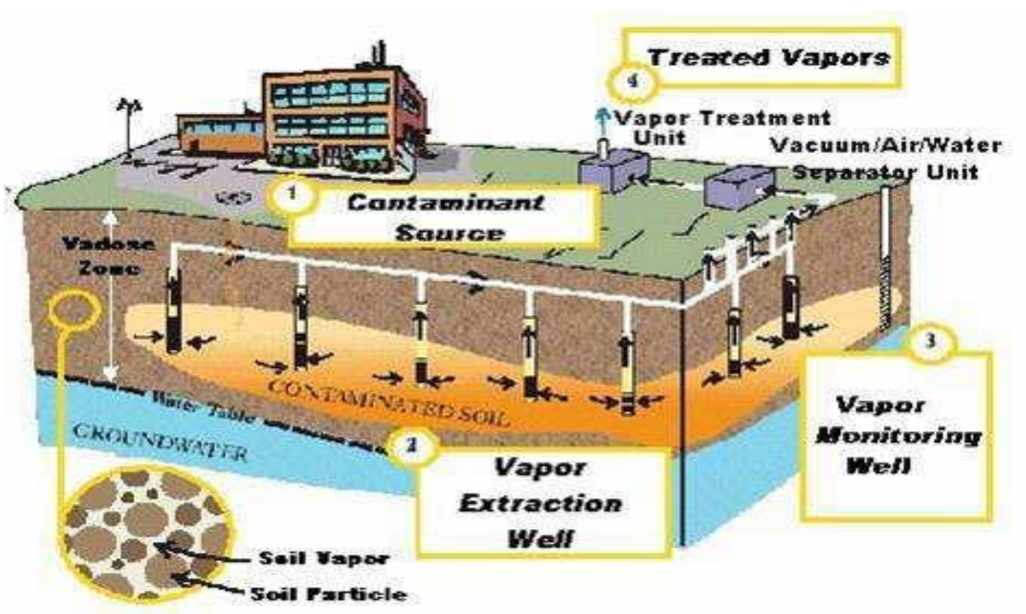

Fig. 7. Typical soil vapor extraction (SVE) site and system [22].

- Bioremediation

As people search for long-term solutions to clean up polluted surroundings, interest in the microbial biodegradation of contaminants has grown recently. Using microbial processes or microbial consortiums to digest and detoxify environmental pollutants is known as bioremediation. It is also one of these new technologies that derive its scientific foundation from the emerging ideas of "green" chemistry and "green" engineering, and it is a rapidly developing, promising remediation technique that is increasingly being researched and used in actual pollutant cleanup applications [23].

Techniques for bioremediation have been utilized to clean up contaminated land ecosystems, freshwater and marine systems, soils, groundwater, and underground soils. To immobilize toxins and convert them into chemical compounds that are no longer dangerous to human health and the environment, most bioremediation technologies were initially designed to remediate petroleum hydrocarbon contamination. Biodegradation products will comprise carbon dioxide, water, and other substances with little harmful environmental effects where contaminants do not significantly endanger the water supply or surface water bodies. By fertilizing (adding nutrients such as nitrogen, carbon, and phosphorus) and sowing adequate microbial populations, bioremediation of soils or any site may be improved. These days, employing organic wastes in bioremediation will be a novel way to encourage and enhance microorganisms to break down organic chemicals [24].

- Phytoremediation

Phytoremediation, or using plants to remediate soil and groundwater, is a relatively new idea, and the technology has yet to be thoroughly tested in the market. Yet, there is a lot of interest in phytoremediation because of its promise for quick, easy, and affordable soil and groundwater remediation. Toxic heavy metals, radionuclides, organic contaminants such as chlorinated solvents, BTEX chemicals, non-aromatic petroleum hydrocarbons, nitrotoluene munitions wastes, and too many nutrients can all be remedied by phytoremediation [25].

Additional uses for phytoremediation include the treatment of industrial effluent and drinking water and the covering of landfills and buffer zones for agricultural runoff. Moreover, phytoremediation may be employed with other treatment technologies as a final polishing step. Although promising, phytoremediation's applicability is constrained by several issues. First and foremost, it's crucial that the potentially contaminated location can sustain plant growth. This calls for an environment with a suitable climate, soils with the proper pH and texture, and enough water and nutrients. Second, because plant roots can only reach a certain depth, phytoremediation is only helpful in superficial pollution (less than 5 m); however, it can occasionally be combined with other methods in cases of deeper contamination. Third, phytoremediation is not appropriate for situations that call for quick treatment since its time requirements are sometimes more significant than those of some traditional treatments, such as landfilling and cremation. Remediation is aided by plants in a number of ways (Fig. 8 shows the Phytoremediation mechanisms):

1. Direct absorption and integration of pollutants into plant biomass
2. Immobilization or phytostabilization of toxins in the subsurface
3. Introduce rhizosphere-bound plant enzymes that attack pollutants directly.
4. Microbes in the rhizosphere are stimulated to degrade organic matter [26].

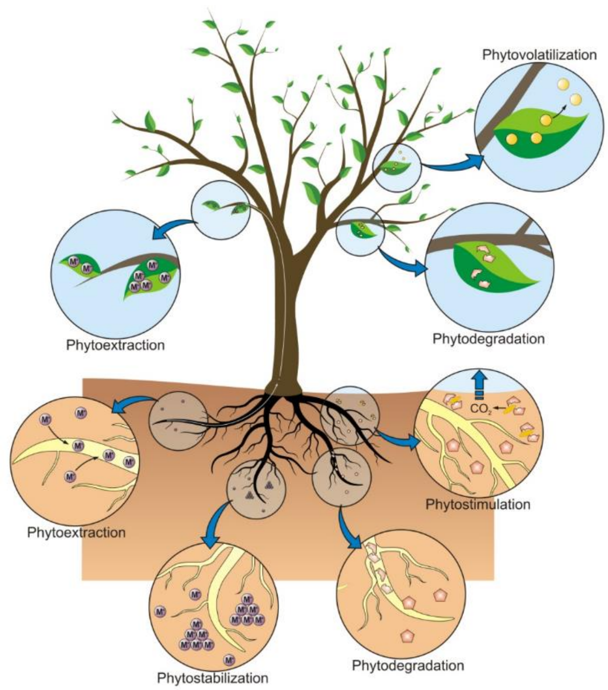

Fig. 8. Phytoremediation mechanisms.

- ✓ Rhizosphere biodegradation: During this process, plants release organic compounds through their roots, feeding soil microbes with nutrients. The microbes accelerate biological decay.
- ✓ Phyto-stabilization: In this procedure, the plant's chemical components immobilize pollutants rather than breaking them down.
- ✓ Phyto-accumulation (sometimes called phytoextraction) is also called phytoextraction. In this procedure, water, nutrients, and contaminants are all absorbed by plant roots. Instead of being eliminated, the contaminated material ends up in the plant's shoots and leaves. Metal-containing trash is the primary use for this technique. One demonstration site uses plant species chosen for their capacity to absorb significant amounts of lead to take up water-soluble metals (Pb). The aerial shoots of the plant, where the metals are housed, are picked and either melted for potential metal recovery or recycling or discarded as hazardous waste.
- ✓ Rhizofiltration is a hydroponic method for cleaning water streams similar to phytoaccumulation but uses plants grown in greenhouses with their roots submerged in water. Treatment of groundwater ex-situ is possible with this technology. To irrigate these plants, groundwater is pumped to the surface. An artificial soil medium, like sand blended with perlite or vermiculite, is typically used in hydroponic systems. The roots are removed and discarded as soon as they are completely saturated with pollutants.
- ✓ Phyto-volatilization: Plants absorb contaminated water that contains organic contaminants in this process, and then the plants release the chemicals into the atmosphere through their leaves.
- ✓ Plant deterioration: Throughout this process, pollutants are metabolized and eliminated within plant tissues.
- ✓ Hydraulic Control: By regulating groundwater flow during this process, trees indirectly remediate. As trees' roots penetrate the ground and form a mass of dense roots that absorb a lot of water, they function as natural pumps [1], [26].

- Biopiles

Bulking agents, fertilizers, and water are added to biopile heaps as part of the soil treatment process. However, the temperatures in static heaps are often close to ambient and not mixed. Using a vacuum or pumping air through the pile might create passive aeration or force it. The bulking agents utilized are often composed of relatively inert materials like sawdust, wood chips, or compost, which support a larger microbial population than soil and offer inorganic nutrients. Periodically, water is introduced as required to maintain the bacteria population [1], [27].

5 NOVEL REMEDIATION TECHNIQUES

- Nanotechnology and remediation
  Nanotechnology has developed a wide range of materials, including those utilized in electrical, optoelectronic, biological, pharmaceutical, cosmetic, energy, catalytic, and material applications. According to a general definition, nanotechnology deals with things that are tiny or materials between 1 and 100 nm in size. Nanotechnology will be modified and applied to improve life quality and length. Nano-materials provide substantial social benefits, and the new products can be used in information technology, healthcare, energy, and the environment. The development of nanotechnology presents many potential environmental advantages [28].
- Dehalogenation
  Dehalogenation is the chemical displacement of a chlorine molecule from organic molecules, which reduces their toxicity.
- Supercritical fluids extraction
  Supercritical fluids are substances with qualities halfway between a gas and a liquid when they are under high pressure and temperature. In these circumstances, the organic pollutant easily dissolves in the supercritical fluid. Emerging innovations in the field of site cleanup include supercritical fluid techniques. There currently needs to be more large-scale applications of supercritical fluids [29].
- Steam stripping
  The mass transfer principle, utilized to transfer volatile pollutants from water to air, is the foundation of the steam stripping technique. Steam is delivered into the soil to evaporate volatile and semi-volatile contaminants through an injection well. Vacuum extraction removes the polluted steam, and then phased separation and condensation are used to remove the impurities [30].
- Ultraviolet (U.V.) oxidation
  As water enters a treatment tank, ultraviolet (U.V.) oxidation technology employs U.V. radiation, ozone, or hydrogen peroxide to eliminate or detoxify organic pollutants. Dechlorinated materials and chlorine gas are the reaction's byproducts.

6 CONCLUSION

In conclusion, environmental remediation is essential to restore the natural balance of our planet's ecosystems. As discussed in this review article, there are numerous examples of ecological disasters caused by human activities. The use of remediation techniques, such as in-situ and ex-situ methods, can help mitigate the negative impacts of these events and ensure that contaminated sites are restored to their natural state. It is important to note that environmental remediation is not a one-size-fits-all solution, and each contaminated site may require a unique approach. However, with the advancement of technology and increased awareness of environmental issues, we are making progress toward developing effective and sustainable remediation techniques. As we move forward, we must continue to prioritize our planet's health and take action to prevent future environmental disasters. By implementing environmentally responsible practices and supporting remediation efforts, we can work towards a healthier and more sustainable future for all.

REFERENCES

[1] Faisal I. Khan, Tahir Husain, Ramzi Hejazi, An overview and analysis of site remediation technologies, Journal of Environmental Management 71 (2004) 95–122, doi:10.1016/j.jenvman.2004.02.003.

[2] Albert T. YEUNG, REMEDIATION TECHNOLOGIES FOR CONTAMINATED SITES, Proc. of Int. Symp. on Geoenvironmental Eng., ISGE2009 September 8-10, 2009, Hangzhou, China

[3] Toxic Waste Dumping in Abidjan: Testimony Project, INTERNATIONAL STATE CRIME INITIATIVE, http://statecrime.org/toxic-waste-dumping-in-abidjan-testimony-project/, (Accessed on April 3, 2023)

[4] Why was Love Canal one of the worst environmental disasters in U.S. history, https://www.britannica.com/place/Love-Canal, (Accessed on April 3, 2023)

[5] American Chemical Society, Chemical and Engineering News:Government & Policy, https://pubsapp.acs.org/cen/government/86/8646gov2.html, (Accessed on 3rd of April 2023)

[6] Greenpeace International, The Toxic Truth, https://www.greenpeace.org/international/publication/7245/the-toxic-truth/, (Accessed on 3rd of April 2023)

[7] Mercury: The Tragedy of Minamata Disease, HealthAndEnvironment.org, https://www.healthandenvironment.org/environmental-health/social-context/history/mercury-the-tragedy-of-minamata-disease, (Accessed on April 3, 2023)

[8] Minamata: Homage to W. Eugene Smith, https://www.nippon.com/en/images/i00051/minamata-homage-to-w-eugene-smith.html, (Accessed on 3rd of April 2023)

[9] What is Environmental Remediation, https://a-otc.com/what-is-environmental-remediation/, (Accessed on 3rd of April 2023)

[10] Arezoo Dadrasnia, N. Shahsavari and C. U. Emenike, Remediation of Contaminated Sites, http://dx.doi.org/10.5772/51591, Chapter 04,2013

[11] What is Environmental Remediation, https://www.bls.gov/green/environmental_remediation/remediation.htm#:~:text=and%20wage%20data.,What%20is%20environmental%20remediation%3F,as%20to%20restore%20the%20environment, (Accessed on 3rd of April 2023)

[12] Saranya Kuppusamy , Thavamani Palanisami , Mallavarapu Megharaj , Kadiyala Venkateswarlu , and Ravi Naidu, Ex-Situ Remediation Technologies for Environmental Pollutants: A Critical Perspective, P. de Voogt (ed.), Reviews of Environmental Contamination and Toxicology Volume 236, DOI 10.1007/978-3-319-20013-2_2, Springer International Publishing Switzerland 2016.

[13] US EPA Office of Superfund Remediation and Technology Innovation (CLU-IN), About remediation technologies. Washington, DC, US EPA (2012)

[14] Sustainability Concern of Contaminated Site Remediation, https://www.slideserve.com/akiva/sustainability-concern-of-contaminated-site-remediation-powerpoint-ppt-presentation, (Accessed on 3rd of April 2023)

[15] Groundwater Pump and Treat, https://frtr.gov/matrix/Groundwater-Pump-and-Treat/, (Accessed on 3rd of April 2023)

[16] Bau DA, Mayer AS, Stochastic management of pump-and-treat strategies using surrogate functions. Adv Water Resour29:1901–1917, (2006)

[17] Federal Remediation Technologies Roundtable, Washington, DC Remediation technologies screening matrix and reference guide version 4.0 – remediation technology, FRTR (2012)

[18] Dushanthi M. Wanninayake, Comparison of currently available PFAS remediation technologies in water: A review, Journal of Environmental Management 283 (2021) 111977, https://doi.org/10.1016/j.jenvman.2021.111977

[19] Alexandratos SD, Ion-exchange resins: a retrospective from industrial and engineering chemistry research. Ind Eng Chem Res 48:388–398, (2008)

[20] Zhengtao Shen, Fei Jin, David O'Connor, and Deyi Hou, Solidification/Stabilization for Soil Remediation: An Old Technology with New Vitality, https://doi.org/10.1021/acs.est.9b04990, Environ. Sci. Technol. 2019, 53, 20, 11615–11617, (2019)

[21] M.A. Hashim a, Soumyadeep Mukhopadhyay, Jaya Narayan Sahu, Bhaskar Sengupta, Remediation technologies for heavy metal contaminated groundwater, Journal of Environmental Management 92 (2011) 2355e2388, doi:10.1016/j.jenvman.2011.06.009, (2011)

[22] M. Mariani, A. Nebbioso, A. Pirone, M.R. Vallerotonda, Distribution of petroleum products for traction: analysis of a reclamation technology, http://sve.ucdavis.edu/TSRTPSVE9-1-05_files/page0002.htm, (2015)

[23] B. Zhao, C.L. Poh, Insights into environmental bioremediation by microorganisms through functional genomics and proteomics, PROTEOMICS, 8 (2008) 874-881.

[24] Baker DB, Conradi MS, N. RE, Explanation of the high-temperature relaxation anomaly in a metal-hydrogen system., Phys Rev B 49 (1994) 11773–11782

[25] Schnoor JL, Licht LA, Mc Cutcheon SC, Wolf NL, C. L.H., Phytoremediation of organic and nutrient contaminants., Environ Sci Technol 29 (1995) 317–323.

[26] J.C. P, Pratas J, Varun M, DSouza R, S. M. Phytoremediation of Soils Contaminated with Metals and Metalloids at Mining Areas: Potential of Native Flora [Internet]. Environmental Risk Assessment of Soil Contamination. InTech; 2014. Available from: http://dx.doi.org/10.5772/57469

[27] Lucian Vasile Pavel, M. Gavrilescu, an overview of ex-situ decontamination techniques for soil cleanup, Environmental Engineering, and Management, 7 (2008) 815-834.

[28] Rajendran P, G. P, Nanotechnology for bioremediation of heavy metals, Environmental bioremediation technologies, (2007) 211–221.

[29] M.D.A. Saldaña, V. Nagpal, S.E. Guigard, Remediation of Contaminated Soils using Supercritical Fluid Extraction: A Review (1994-2004), Environmental Technology, 26 (2005) 1013-1032.

[30] M.M. Amro, Treatment Techniques of Oil-Contaminated Soil and Water Aquifers, International Conf. on Water Resources & Arid Environment, (2004) 1-11.