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Soil Contamination in the Aftermath of Industrial Disasters: Risk Assessment and Crisis Management

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Abstract: Industrialisation has brought numerous benefits to society, but it has also led to environmental challenges, including the risk of industrial disasters. Industrial disasters pose significant risks to environmental health, with soil contamination emerging as a prevalent consequence. The resultant contamination renders affected sites barren and unsuitable for reuse, necessitating the treatment of such sites post-disaster to restore soil functionality and ecosystem. In this context, the review proposes an appropriate approach to carry out risk assessment studies of contaminated sites and to discuss strategies for the post-disaster management of contaminated soil. The review delves into the policy and legislative landscape governing industrial disaster management in India to facilitate progress in the remedial direction.

Key words: Industrial disaster, disaster management, soil contamination, heavy metals.

Introduction

An increase in soil contamination has been observed in recent years, owing to the rapid growth in the industrial sector (Taneja et al., 2024). The evolution of chemical industries has led to an increase in the risk of hazardous chemicals-associated accidents. The National Disaster Management Guidelines on chemical disasters define a chemical disaster as "an occurrence including any particular major emission, fire or explosion involving one or more hazardous chemicals and resulting from uncontrolled developments in the course of industrial activity or transportation or due to natural events leading to serious effects both immediate or delayed, inside or outside the installation likely to cause substantial loss of life and property including adverse effects on the environment" (NDMG, 2007). Since this study is concerned with the chemicals released from industrial accidents/disasters, the term 'chemical disasters' has been used interchangeably with 'industrial disasters.' Some examples of major chemical disasters include Bhopal Gas Tragedy (1984) due to an accidental leak of toxic gas, Methyl Isocyanate (Sriramachari, 2004); the gas explosion at Indian Petrochemicals Corporation Limited, Maharashtra (1990) and Hindustan Petroleum Corporation Limited refinery, Vishakhapatnam (1997); Fire in an oil well in Andhra Pradesh (2003); oil spills; release of toxic industrial waste and poisoning (Minamata disaster), etc. (Ojha and Rahman, 2023).

Occurrence of chemical or industrial accidents is either due to human errors such as negligence in following the safety protocols, poor planning, and non-compliance, or due to system failures such as design defects, corrosion, damage, etc. which can cause significant immediate or long-term damage to the environment and public health (Gupta and Nair, 2012).

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Thus, these disasters can be avoided or minimized through proper preparedness and emergency response. There are guidelines and emergency plans released by the Government of India (GOI) suggesting preventive measures to eliminate the risk of industrial hazards or to mitigate the effects (NDMG, 2007), however, there is a lack of access to proper tools to assess and remediate the contaminated regions in the aftermath of an industrial disaster, which is critical to ensure minimum economic losses and quick recovery of the site. In this context, this paper presents an overview of the policies and legislations laid out by the GOI to tackle the industrial crisis. This study aims to provide a suitable risk assessment approach for rapid and effective remediation of affected sites. Finally, the paper explores a few site remedial techniques based on their ability to reduce health risks posed by the contaminated site to form an effective mitigation strategy.

Impacts of Industrial Disasters on the Environment and Human Health

The substances released from the industrial hazards can be organic compounds like dioxin, PAHs, PFAS, and other complex hydrocarbons, or inorganic compounds like toxic heavy metals (Finnecy, 1987). When released, these pollutants interact among the environment's different components and ultimately enter the soil (Figure 1). Heavy metals, such as lead, mercury, cadmium, and arsenic, are common pollutants in soil following industrial accidents due to their widespread use in industrial processes, such as paints and pigment manufacturing, battery manufacturing, electroplating, mining and metallurgical processes, etc. (Khalid et al., 2017). Oil spills, industrial effluent discharge, improper disposal of toxic waste, and accidental leaks release heavy metals in the soil, which results in reduced

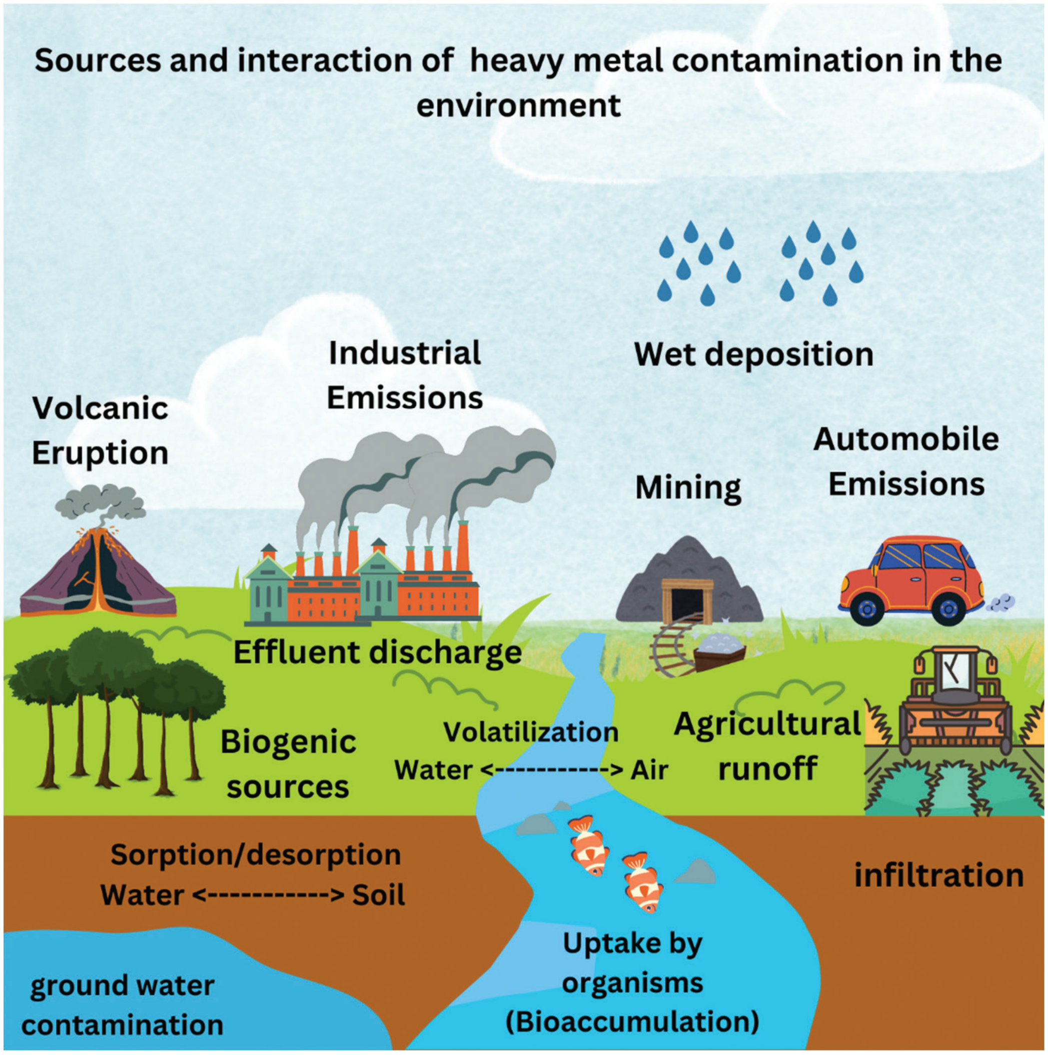

Figure 1: Major sources and interaction of heavy metals in the environment.

soil fertility, disrupted rhizosphere functioning, and alteration in microbial composition. Owing to the non-degradability and persistence of heavy metals, they tend to remain in the soil for prolonged periods, posing a serious risk of entering the food chain. The uptake of metals by crops causes oxidative damage to the plants, and modifies the normal biosynthesis pathways, thereby affecting agricultural productivity and food security (Deepika and Haritash, 2023).

The duration of the persistence of metals in the soil increases the risk of groundwater pollution through leaching (Taneja et al., 2023). Heavy metal pollution not only affects soil quality and plant growth but also has grave consequences on human health such as renal dysfunction, liver damage, gastrointestinal haemorrhage, pulmonary diseases, DNA alterations, etc (Table 1). The interaction of metals with different environment matrices decides the exposure route and frequency to humans, which is vital to assessing health risks (Wuana and Okieimen, 2011).

Policy and Legislation for Industrial Disaster Management in India

India has a long history of coping with natural calamities like floods, droughts, earthquakes, etc. However, with the industrial revolution and increasing population, the complexity of disasters outpaced the existing traditional response mechanisms of the communities. The genesis of man-made disaster management in India evolved dramatically after the Bhopal Tragedy incident in 1984 (Keim, 2018). However, way before the accident, the Indian Government had a legal regulatory framework on chemical safety and management under the acts Factories Act, 1948, Explosives Act, 1934, and The Petroleum Act, 1934. These rules were laid down to regulate industrial mishaps and cover the safety in transportation, liability, compensations, insurance, etc. This approach was reactive and focussed on the response and relief in the aftermath of disaster (Behera and Hassan, 2019). Nevertheless, with the advent of modernisation and increasing industrial disasters, a paradigm shift was observed with the formalisation and enactment of the Disaster Management Act in 2005, where the main goal was to strengthen the prevention and preparedness phase of disaster management with the establishment of this legislation at national, state, and local levels. Under this act, key bodies were formed, namely, National Disaster Management Authority (NDMA), State Disaster Management Authority (SDMA), and District Disaster Management Authority (DDMA). These bodies are responsible for implementing disaster management programs, assessing risks, developing plans and guidelines, and coordinating with response and recovery in the affected regions (Behera and Hassan, 2019).

The country has made significant strides in promoting its preparedness and resilience to disasters through a strong legal framework. However, challenges remain in managing industrial disasters and addressing site contamination issues, for instance, inadequate enforcement of regulations, insufficient monitoring, and lack of availability of case studies of major accidents at the national level.

Table 1: Selected heavy metals, their sources, and toxic response to human health

Metals	*Industrial sources*	*Effects on Human Health*	*References*
Cu	Industrial waste pipes Additives Fungicides	Cystic fibrosis Insomnia Wilson disease Kidney damage	Wuana & Okieimen, 2011
Cd	Electroplating Batteries Fertilizers	Renal dysfunction Coronary heart disease Osteomalacia	Genchi et al., 2020
Cr	Timber treatment Leather tanning Dyes	Gastrointestinal haemorrhage Pulmonary fibrosis DNA alteration	Pavesi & Moreira, 2020
Pb	Batteries Paints	Kidney failure Intestinal damage Cardiovascular diseases	Silva et al., 2018

Crisis Management Post-Industrial Disaster

Crisis or disaster management is a process of identifying the hazard, assessing the impacts associated with the concerned hazard, in terms of losses and health risks, and finally providing a framework to monitor, evaluate, and mitigate the adverse outcomes of the disaster. A comprehensive management plan consists of three main components: site characterisation; health risk assessment and; suitable remedial actions based on the risk assessment studies to recover and re-use the site for different purposes (Figure 2).

Site Characterisation

The foremost task post-industrial accident is the collection of data conforming to the site and the nearby region. It includes the determination of characteristics of the site including the properties of soil, groundwater, surface water, and the contaminants present (Guerriero et al., 2020). It involves, first, the identification of the type of hazard or contaminant, followed by the source or origin of the contaminant, for instance, the release of toxic hexavalent chromium from the accidental leakage of electroplating industry effluent. After identification, a hazard assessment is performed, which includes quantification of the concentration of contaminant released, and the extent and magnitude of contamination over the site (Wcisło, 2021).

Health Risk Assessment

Human health risk assessment (HRA) is a method to estimate the potential adverse effects of a hazard to humans who are exposed to contaminants (Zhang et al., 2023). HRA plays a crucial role in the selection of appropriate remedial techniques by assessing the magnitude and probability of contaminant exposure to humans. After establishing the baseline data concerning the contaminant on-site, the interaction of the contaminant with humans is quantified in three key steps of HRA: exposure assessment; toxicity assessment, and; risk characterisation (Chakraborty et al., 2021).

Exposure Assessment

Exposure assessment is the process of assessing the extent, frequency, and duration of human exposure to contaminants. The exposure is determined based on exposure scenarios through potential migration pathways. There are mainly three receptor routes through which exposure is possible: ingestion, inhalation, and dermal. Direct exposure occurs through inhalation of contaminated air, or dermal exposure through the surface area of skin (Banerjee et al., 2023; Wu et al. 2022). Whereas, indirect exposure occurs when the contaminants are transferred from the contaminated media, as in the case of incidental ingestion. These routes of exposure determine the contaminant intake by humans.

Toxicity Assessment

Toxicity assessment is a method of estimating the adverse effects of exposure to a particular contaminant (USEPA, 2002). It takes into account the toxicological profile of the contaminant to assess the dose-response relationship. To perform a toxicity assessment, baseline data, for example, reference doses (R*f*D) and slope factors (SF), etc., are crucial, that reflect the minimum level of exposure that would cause no adverse effects (Ghosh et al., 2023). Other parameters such as gastrointestinal absorption, inhalation unit risks, etc. are also required to analyze the interaction and the toxicological effects of contaminants from environmental media to the primary target organs.

Risk Characterisation

Risk characterisation is a product of the outputs of exposure as well as toxicity assessment which depicts the overall health impact in terms of carcinogenic, non-carcinogenic, and radiological risks. Non-carcinogenic risk is estimated by calculating the Average Daily Dose (ADD, mg/kg/day) of a contaminant through all three routes of exposure pertaining to the days of exposure (Eq. 1-3). The ADD is then calculated against the R*f*D to obtain the Hazard Quotient (HQ) (Eq. 4). The sum of HQ from the three pathways is the Hazard Index (HI) (Eq. 5), which determines the non-cancer risks associated with a contaminant, with HI<1 will have no adverse effects, and HI>1 will have potential adverse non-carcinogenic effects. Carcinogenic risks, on the other hand, are estimated through the product of ADD with the slope factor (SF) (Eq. 6-8). Total carcinogenic risk is estimated from the sum of risks from the three pathways (Eq. 9). The normal value of TCR ranges from 10^{-6} to 10^{-4}, above which, the associated contaminant poses an adverse carcinogenic risk (Narsimha et al., 2020).

$$AD\,\mathrm{Dig} = \frac{C \times IngR \times EF \times ED \times EF}{BW \times AT} \tag{1}$$

$$AD\,\mathrm{Dinh} = \frac{C \times Ingh \times ED \times EF}{BW \times AT \times PEF} \tag{2}$$

$$AD\,\mathrm{Dder} = \frac{C \times ESA \times AF \times ED \times EF}{BW \times AT} \times 10^{-6} \tag{3}$$

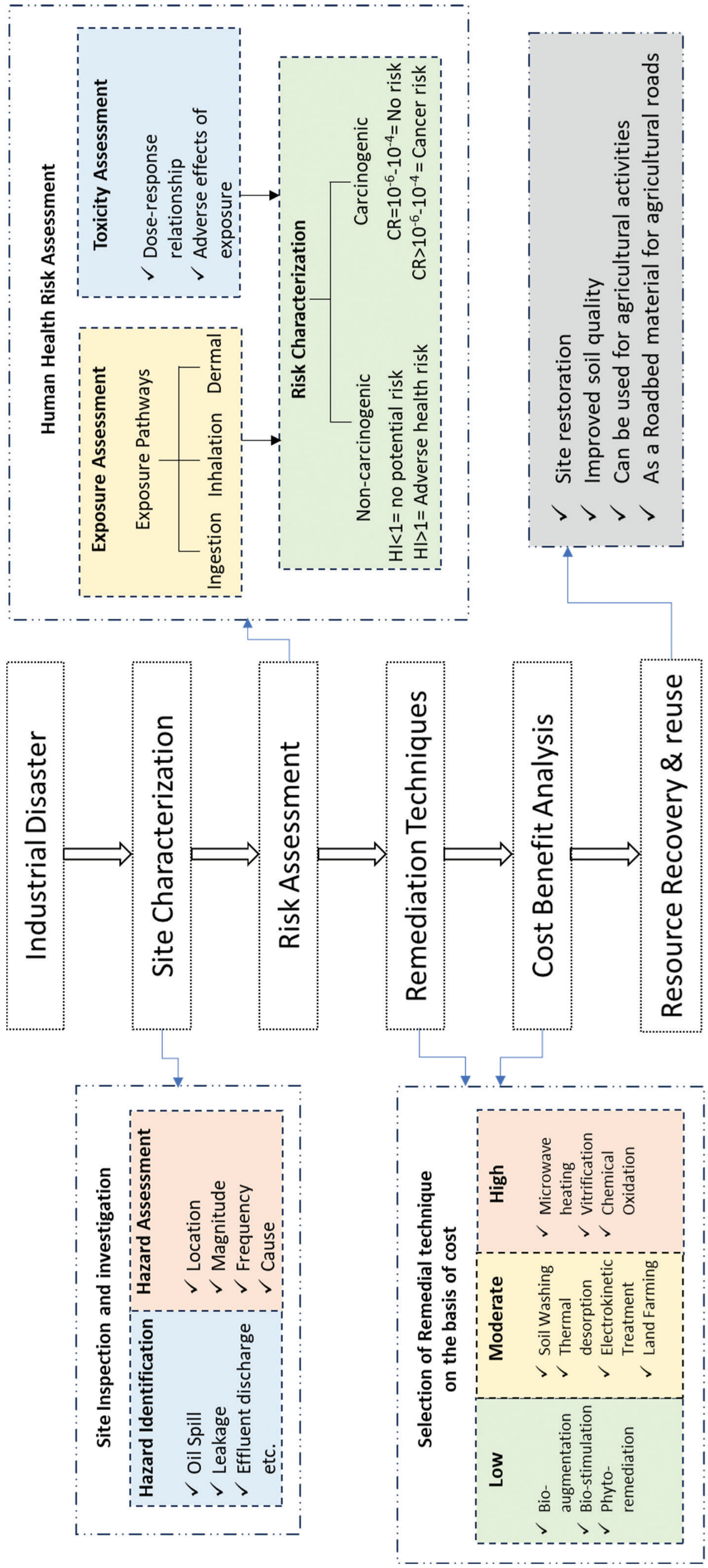

Figure 2: Crisis management process for metal-contaminated sites in the aftermath of industrial disaster.

$$HQ = \frac{ADDi}{RfDi} \quad (4)$$

$$HI = \sum HQHI \quad (5)$$

$$C\ \text{Ring} = AD\ \text{Ding} \times S\ \text{Fing} \quad (6)$$

$$C\ \text{Rinh} = AD\ \text{Dinh} \times S\ \text{Fing} \quad (7)$$

$$C\ \text{Rder} = AD\ Dder \times SF\ der \quad (8)$$

$$TCR = \sum(C\ \text{Ring} + C\ \text{Rinh} + C\ \text{Rder}) \quad (9)$$

where C is the soil heavy metal concentration (mg/kg); IngR (mg/day) and InhR (m^3/day) are the ingestion and inhalation rates of soil particles, respectively; EF (day/year) and ED (year) are the exposure frequency and exposure duration, respectively; BW and AT are the average body weight of the exposed individual (Kg) and average exposure time (day), respectively; ESA is the exposed skin surface area (cm^2); AFS is the skin adherence factor (mg/cm^2); PEF is the particle emission factor (m^3/kg). R*f*D is the reference dose (mg/kg/day), and "i" is the number of exposure pathways.

Selection of Remedial Technique

The selection of suitable remediation alternatives is done based on risk assessment data. The removal of metals from soil depends mainly on the properties of the soil which influence the degree of soil-metal binding (Bolan et al., 2014). In the case of fine-grained soil, techniques like soil washing are not successful due to the low permeability of such soils which does not allow the washing agents to uniformly act (Yeung et al., 1997). Similarly, alkaline soils with high pH promote adsorption and complexation of metals with soil rendering it difficult to treat such soils (Al-Hamdan and Reddy, 2008). The efficiency of the selected remediation technique will govern the HRA post-treatment. Various site remediation technologies can be employed for post-disaster reclamation, which can be divided into physical, chemical, and biological methods, as discussed below:

Immobilisation Strategies

Physical methods like surface capping, solidification/stabilisation, and vitrification focus on immobilising or containing metals (Wuana and Okieimen, 2011). The surface capping method effectively mitigates the potential hazards associated with direct contact with contaminated soil, such as skin exposure or unintentional ingestion. The surface cap functions as an impermeable barrier that hinders the infiltration of surface water, hence preventing the diffusion of soil pollutants into both surface water and groundwater. The soil that has been capped, however, experiences a loss of its inherent environmental functions, particularly in its ability to support plant development (Liu et al., 2018). The solidification method is a process that entails introducing binding agents to a contaminated substance to confer physical and dimensional stability. This stability serves to confine the contaminants within a solid product and minimise their exposure to external agents. This is achieved through a combination of chemical reactions, encapsulation, and the reduction of permeability and surface area (Tajudin et al., 2016). The process of stabilisation, also known as fixing, entails the introduction of specific reagents into the soil that is polluted to generate elements that are chemically more stable. The binding agents most frequently employed in the solidification/stabilisation (S/S) technique are typically inorganic, including clay minerals like bentonite, fly ash, calcium carbonate, cement, iron/manganese oxides, blast furnace slag, charcoal, and zeolite. Additionally, organic stabilisers such as composts, bitumen, and manures may be used, either individually or in conjunction with inorganic amendments. The primary means by which metals are rendered immobile is by the process of hydroxide precipitation occurring inside the solid matrix (Shen et al. 2019).

Vitrification, akin to S/S, employs thermal treatment rather than chemical additions to decrease the mobility of metals with a high-temperature treatment, typically over 1500°C. Ballesteros et al. (2017) conducted vitrification of industrial waste that transformed Cr^{6+} to Cr^{3+} and achieved effective immobilisation of the highly toxic waste. Vitrification is a technology that exhibits high efficiency; nonetheless, this method is not suitable for soils with high organic matter content, high moisture content, or are polluted by volatile or combustible organic substances. The bioavailability of metals can be diminished using immobilisation techniques, although it is important to note that long-term stability cannot be assured and may potentially result in future re-contamination. Hence, it is imperative to devise a removal method that can effectively and permanently extract metals from soil.

Mobilisation/Extraction Strategies

The remediation techniques employed for soil contaminated with metals mostly involve the mobilisation of metals, followed by extraction. These include soil washing/flushing, phytoextraction, and electrokinetic remediation. The soil washing/flushing method is employed for the permanent extraction of metals from coarse-grained soils, particularly those that are significantly contaminated, such as abandoned smelting and electroplating-affected soil (Reddy et al., 2010). Soluble metal ions contained in the pore fluid are effectively extracted from soil by passing a suitable extraction fluid through it. The selection of the optimal concentration and volume of extraction is a crucial factor to be taken into consideration to prevent any potential toxicity. This approach is exclusively suitable for homogeneous soils with coarse textures and high permeability (Popescu et al., 2017).

Phytoextraction is a remediation technique that utilises the natural capabilities of green plants to extract heavy metals from contaminated environments (Deepika and Haritash, 2023). To achieve this objective, it is advantageous to utilise hyperaccumulator plants such as sunflower and tobacco, among others (Cameselle et al., 2013). The aforementioned technology, which is derived from plant sources, exhibits operational simplicity, aesthetic desirability, economic viability, and widespread acceptance. In contrast to physical and chemical interventions that cause permanent modifications to soil characteristics, phytoremediation typically enhances the physical, chemical, and biological attributes of polluted soils. Nevertheless, this technique has several drawbacks concerning extended processing time and a relatively low rate of elimination (Siyar et al., 2020).

Electrokinetic remediation (EKR) is a physico-chemical technique that utilises the application of an electric field to facilitate the movement of metal pollutants from the soil matrix (Taneja et al., 2024). Due to its capacity to be employed on soils with varying compositions and low permeability, the application of EKR exhibits extensive practical utility. It is a well-suited in-situ remediation method that yields excellent removal efficiency with moderate cost inputs (Taneja et al., 2023).

Challenges and Future Prospects

Soil contamination resulting from industrial disasters poses significant impacts to environmental and human health. Thus, soil investigations and subsequent mitigation efforts should be prioritised. The assessment of the possible health impact of contaminated sites is, in many cases, a big challenge, especially where complex contamination and long-lasting human exposures occur. In this context, a risk assessment is an important tool that may support the decision-making process associated with soil remediation. However, despite regulatory frameworks, challenges remain in effectively managing industrial disasters due to inadequate enforcement of regulations, insufficient monitoring and surveillance systems, and gaps in coordination among relevant stakeholders. Hazard and risk assessment information to first responders, harmonised risk assessment and management principles and case studies of accidents/major accidents/disasters in hazard units are not available.

Addressing these challenges requires a multi-faceted approach encompassing effective disaster management policies, robust regulatory frameworks, and innovative soil remediation techniques. Engaging local communities in soil remediation efforts is crucial for ensuring the success and sustainability of remediation projects. Capacity-building initiatives, including training programs and awareness campaigns, empower communities to participate actively in soil management and restoration activities.

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