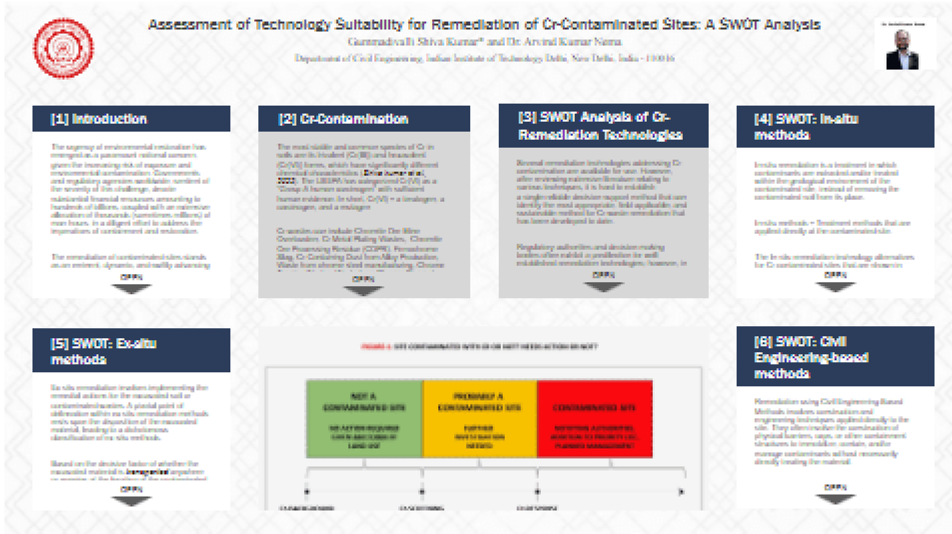
Assessment of Technology Suitability for Remediation of Cr-Contaminated Sites: A SWOT Analysis



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[1] INTRODUCTION

The urgency of environmental restoration has emerged as a paramount national concern, given the increasing risk of exposure and environmental contamination. Governments and regulatory agencies worldwide, sentient of the severity of this challenge, devote substantial financial resources amounting to hundreds of billions, coupled with an extensive allocation of thousands (sometimes millions) of man-hours, in a diligent effort to address the imperatives of containment and restoration.

The remediation of contaminated sites stands as an eminent, dynamic, and swiftly advancing discipline within the realm of environmental restoration. Contaminated sites often exhibit a complex amalgamation of pollutants, constituting mixtures of petroleum hydrocarbons, halogenated organic compounds, H-acid (a dye intermediate) related, metals and metalloids, radionuclides, pesticides, explosives, etc. (*Panagiotakis and Dermatas, 2015; Ramachandran and Muralikrishna, 2000*).

Anthropogenic activities associated with heavy metals (such as metal mining, mineral processing, industrial applications, and consumer usage) have expanded over the past few decades and contributed significantly to heavy metal contamination.

Among the commonly utilized metals, Chromium (Cr) is known for its high contamination potential, acute toxicity, and onerous remediation requirements.

[2] CR-CONTAMINATION

The most stable and common species of Cr in soils are its trivalent (Cr(III)) and hexavalent (Cr(VI)) forms, which have significantly different chemical characteristics (*Shiva kumar et al., 2022*). The USEPA has categorized Cr(VI) as a “Group-A human carcinogen” with sufficient human evidence. In short, Cr(VI) = a teratogen, a carcinogen, and a mutagen

Cr-wastes can include Chromite Ore Mine Overburden, Cr-Metal Plating Wastes, Chromite Ore Processing Residue (COPR), Ferrochrome Slag, Cr-Containing Dust from Alloy Production, Waste from chrome steel manufacturing, Chrome Tanning Wastes, Waste from Chrome Pigment Production, Cr-Residues from Refractory Production, etc (*Dhal et al., 2013*). Among all the anthropogenic Cr-wastes, COPR, sometimes known as Chromite ore processing waste (COPW), has been considered one of the most environmentally hazardous industrial Cr-wastes, presenting risks to human health and the environment (*Shiva kumar and Nema, 2019*).

Several past studies have revealed that numerous issues need addressing in the management, containment, and remediation of Cr-containing wastes. The intricate nature of the chemical compositions, coupled with the elevated potential for exposure risks at Cr-contaminated sites, necessitates an immediate imperative for their remediation. This imperative, in turn, underscores the exigency for the expeditious development of technologically sophisticated and efficacious remediation solutions.

Consequently, safe, reliable, efficient, effective, and scientific management (and disposal) of Cr-wastes is an urgent necessity, especially at the legacy contaminated sites where Cr-waste is the predominant pollution source.

It should be noted that the technology options that focus on managing soil contamination resulting from Cr-wastes vary considerably when compared to the technology alternatives that aim for the treatment and remediation of Cr-waste itself.

Figure 1 shows the levels by which any site having chromium can be marked as a Cr-contaminated site; and whether it needs any remediation action or not.

[3] SWOT ANALYSIS OF CR-REMEDIATION TECHNOLOGIES

Several remediation technologies addressing Cr-contamination are available for use. However, after reviewing extensive literature relating to various techniques, it is hard to establish a single reliable decision-support method that can identify the most appropriate, field-applicable, and sustainable method for Cr-waste remediation that has been developed to date.

Regulatory authorities and decision-making bodies often exhibit a predilection for well-established remediation technologies; however, in the case of COPR, the remediation solutions (as they are not fully mature [commercially]) prove to be inadequate in fulfilling the regulator's objectives. Consequently, the urgency of the situation mandates further developmental efforts and a heightened emphasis on additional research to address the identified shortcomings.

Stabilization/solidification, which is considered the best field applicable remediation process by USEPA, is proved to be ineffective, as cement stabilization of COPR leads to excessive ettringite heave (rendering zero post-remedial commercial value to the site).

There exists a high need to assess the "advantages and disadvantages", "strengths and weaknesses", "beneficial and negative impacts", and "gains and losses" of using a particular remediation technique for Cr-contaminated sites above others. Therefore, the current study adopts a "SWOT Analysis" as a decision-support tool to attain the objective of examining the advantages and disadvantages of various remediation techniques.

SWOT = Strengths, Weaknesses, Opportunities, and Threats

In this regard, the entire list of techniques applicable for the remediation of Cr-contaminated sites (generated from an extensive literature survey) is divided into three sub-groupings [*division is based on how and where the remediation method is applied*]:

1. In-situ methods
2. Ex-situ methods
3. Civil Engineering-based methods

Figure 2 shows how the present study [i.e., using a SWOT Analysis] harmonizes with the process of environmental remediation of contaminated sites. Conversely, the entire list of available remediation techniques that are applicable to Cr-contaminated sites is presented in **Figure 3**.

SWOT assessment is intended for use in the preliminary stages of the decision-making process. It has to be considered as a 'starting point' for the discussion; and, in itself, cannot help researchers understand:

- "What is the best remediation alternative?"
- "how a remediation technology alternative can achieve a competitive advantage over another?"

Though criticized for its limitations, SWOT Analysis has been described as a tried-and-true tool of strategic analysis by several researchers and industrialists.

[4] SWOT: IN-SITU METHODS

In-situ remediation is a treatment in which contaminants are extracted and/or treated within the geological environment of the contaminated site, instead of removing the contaminated soil from its place.

In-situ methods = Treatment methods that are applied directly at the contaminated site.

The In-situ remediation technology alternatives for Cr-contaminated sites that are shown in Figure 3 were assessed for their various "Strengths, Weaknesses, Opportunities, and Threats" as part of the SWOT Analysis. Accordingly, the identified aspects of these In-situ remediation methods are presented in **Figure 4**.

Apart from various aspects of In-situ remediation technologies (as found via SWOT analysis), several site constraints, remediation criteria, and contaminant characteristics at the site must be considered before decision-making. For example, according to *Shukla et al. (2019)*, COPR has a very high buffering capacity. Thus, the addition of organic matter and pH adjustments are not feasible or cost-effective for in-situ applications, especially at COPR-contaminated sites with high Cr-waste (both, quantity and concentration).

[5] SWOT: EX-SITU METHODS

Ex-situ remediation involves implementing the remedial actions for the excavated soil or contaminated wastes. A pivotal point of delineation within ex-situ remediation methods rests upon the disposition of the excavated material, leading to a dichotomous classification of ex-situ methods.

Based on the decisive factor of whether the excavated material is ***transported*** anywhere or remains at the location of the contaminated site, ex-situ methods are delineated into two distinct categories:

1. Off-site treatment
2. On-site treatment

Ex-situ methods = Excavation + Treatment method application

Ex-situ remediation involves excavation, transport, and handling of contaminated material.

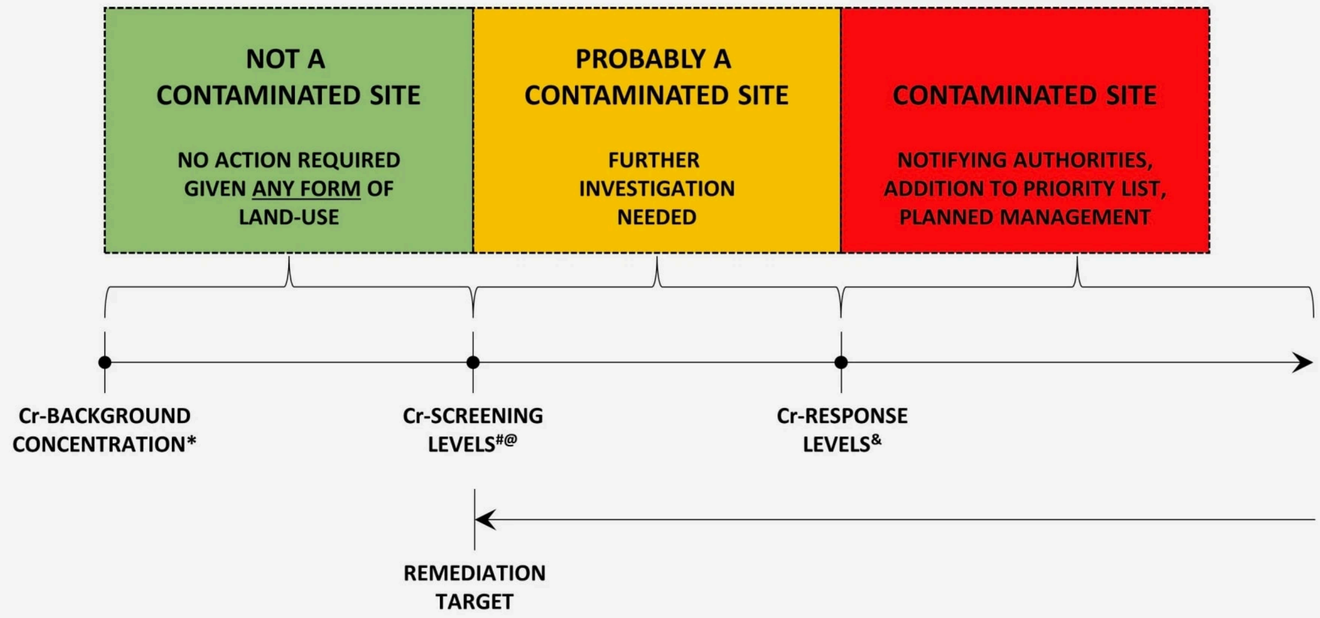
Off-site treatment = involving the excavation of the polluted soil/waste; and, the subsequent treatment in a controlled waste- or soil-cleaning installation

On-site treatment = Same as Off-site treatment with the difference that the soil-cleaning installation would be situated on the location of the contaminated site

Following a comprehensive SWOT analysis, an array of facets pertaining to ex-situ remediation methods were identified and are clearly elucidated in **Figure 5**.

Compared to in-situ methods, in the majority of cases, Ex-situ remediation technologies can be more expensive and time-consuming due to excavation, transportation, and treatment processes. However, Ex-situ methods provide better control over treatment conditions, potentially leading to higher treatment efficiency.

FIGURE-1: SITE CONTAMINATED WITH CR OR NOT? NEEDS ACTION OR NOT?



NOTE:

*No background concentrations should be used for certain contaminants [such as Persistent Organic Pollutants (POPs)], as there is no natural background for these substances

#Concentrations levels of contaminants (*in soil and sediments, groundwater and surface water*) at or below which potential risks to human health or the environment are not likely to occur and where no further investigation and assessment is needed

& Concentrations levels of contaminants (in soil and sediments) at or above which it is very likely there is a threat to human health or the environment, that may be imminent. At or above this level some form of response is required to provide an adequate level of safety to protect public health and/or the environment

@Screening levels are different for different land use

FIGURE-2: SWOT Analysis of Remediation Technologies

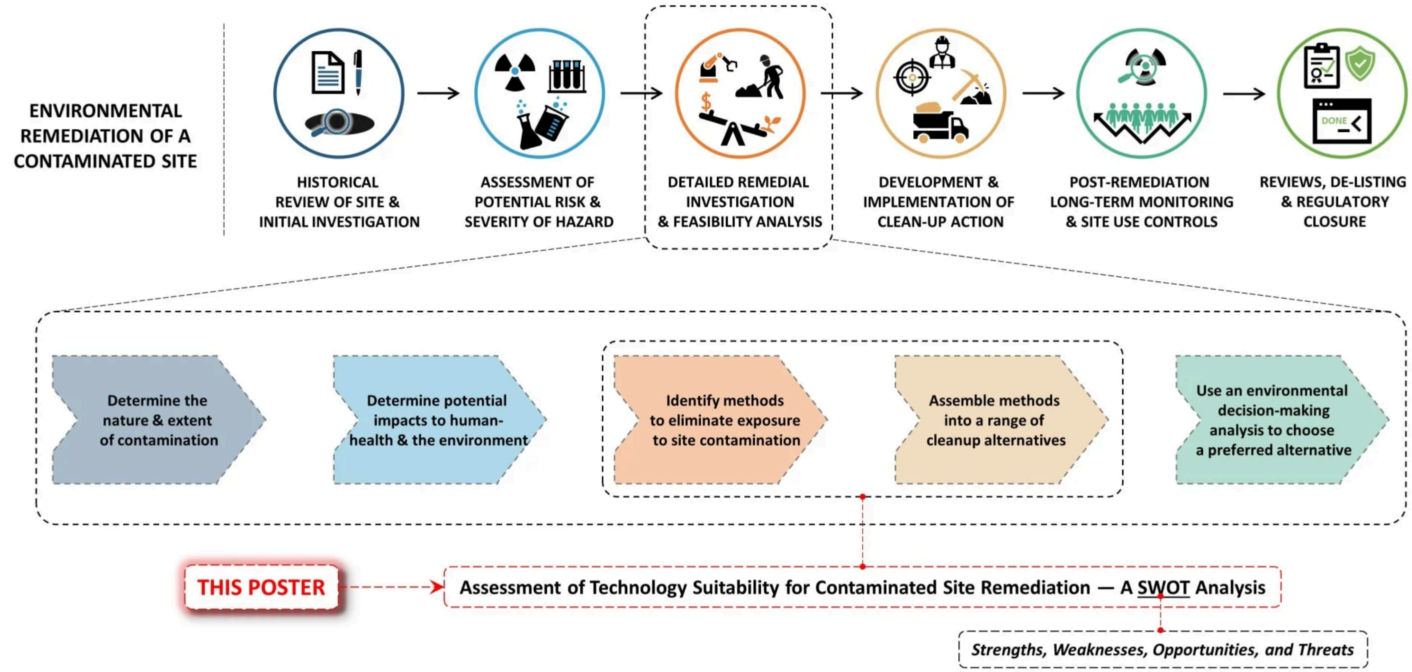


Figure 3: Classification of Contaminant Remediation Technologies by Process

<table>
<tr><td colspan="4">*In situ* - Remedial activities taking place in the subsurface</td></tr>
<tr><th>Biological</th><th>Physical</th><th>Chemical</th><th>Thermal</th></tr>
<tr><td colspan="3">Permeable reactive barriers (PRBs)</td><td>Thermal treatment</td></tr>
<tr><td colspan="3">Flushing</td><td></td></tr>
<tr><td>Enhanced bioremediation</td><td></td><td>Chemical oxidation and reduction*</td><td></td></tr>
<tr><td></td><td></td><td>Chemical Immobilization</td><td></td></tr>
<tr><td>Phytoremediation</td><td colspan="2">Electro-remediation</td><td></td></tr>
<tr><td>Monitored natural attenuation</td><td colspan="2">Stabilization/solidification (S/S)</td><td></td></tr>
<tr><td colspan="2">Sparging</td><td></td><td></td></tr>
<tr><td colspan="2">Venting</td><td></td><td></td></tr>
<tr><td></td><td colspan="3">Vitrification</td></tr>
<tr><td colspan="4">*Ex situ* - Remedial actions applied to excavated soil or the treatment at the surface of contaminated water or gaseous emissions</td></tr>
<tr><th>Biological</th><th>Physical</th><th>Chemical</th><th>Thermal</th></tr>
<tr><td>Biological treatment#</td><td colspan="2">Soil washing and separation processes</td><td>Thermal desorption</td></tr>
<tr><td>Bioreactor systems/ treatment cells</td><td colspan="2">Stabilization/solidification</td><td></td></tr>
<tr><td></td><td colspan="2">Venting</td><td></td></tr>
<tr><td></td><td colspan="2">Electro-chemical technologies</td><td></td></tr>
<tr><td></td><td></td><td>Chemical treatment (Redox)@</td><td></td></tr>
<tr><td></td><td colspan="3">Vitrification</td></tr>
<tr><td></td><td colspan="3">Pyrometallurgical treatment</td></tr>
<tr><td colspan="3">Water and gas/vapour treatment</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Pyrolysis</td></tr>
<tr><td colspan="4">**Civil engineering-based methods –** e.g. excavation/abstraction, hazardous waste (secured) landfilling, vertical wall, containment measures (i.e., capping layer such as soil cover, membrane layer treatment, etc.)</td></tr>
</table>

Note— *Generally, transforming Cr(III) to Cr(VI) during oxidation (e.g., soil flushing) or Cr(VI) to Cr(III) during reduction (e.g., PRBs); #Only in certain variations of bioremediation such as landfarming or biopiles of excavated contaminated material; @Cr(VI) reduction to Cr(III) during the implementation of contaminant immobilization or toxicity reduction (e.g., treatment with ferrous salts, sulfides, nZVI, etc.), and Cr(III) oxidation to Cr(VI) during resource recovery (e.g., treatment of contaminated material with manganese oxides, aerobic heating, electrochemical oxidation, etc.).

Figure 4: **SWOT Analysis of In-situ** (*Treatment method applied directly at site*) **Remediation Alternatives for Cr-contaminated sites**

Remediation Technology Alternatives	**SWOT Analysis**			
	Strengths	**Weaknesses**	**Opportunities**	**Threats**
Electro-remediation (Electrokinetics)	• This technique is able to in-situ remediate heavy metals	• Most often limited to small areas/volumes of contamination • Its application should be well evaluated beforehand	• Very suitable for a target remediation of small, isolated heavy metal contaminations	• Extremely high cost-intensive process (Capital and O&M) • High energy requirements • local conditions strongly influence the success of a full-scale application
In-situ chemical treatment	• Heavy metal remediation was proven effective at some sites. • Suitable for remediating source areas as well as plume areas of contamination	• Non-selective remediation process • Oxidizing agents will also react with soil's non-hazardous components	• Transforming Cr(III) to Cr(VI) during oxidation (e.g., soil flushing) or Cr(VI) to Cr(III) during reduction (e.g., PRBs)	• Chemical costs are extremely high due to interferences. • Too much oxidant is applied resulting in unexpected and unwanted reactions
Permeable Reactive Barriers (PRB)	• Very low operational costs • High remediation levels can be achieved for plumes. • Long-term working of the system • Can remediate a wide variety of contaminants	• Do not provide a permanent remediation solution for a source area of contamination. • Require skills on hydrological conditions of the area	• Sustainable alternative (especially for aquifer contaminations)	• Require a high-quality monitoring of the system and the surrounding areas as changes in hydrological conditions can occur during the long term a PRB is in operation
In-situ enhanced bioremediation	• Uses microbial cultures for remediation purposes. • Can remediate Cr, if present in low concentrations	• Requires a lot of specific investigations on items not common within the soil investigation. • Remediation contractors are patenting various nutrient compositions limiting their use	• Very suitable for contaminated sites where there are no time restrictions	• Requires a high quality of investigation data and monitoring. • Needs specific microbial strains for effective treatment. • High variability of success
Phyto-remediation	• Well suited to remediating large areas having shallow contamination. • The plants used for Phyto-remediation enhance the green appearance of a site. • If well-designed, it can tackle low to moderate Cr levels	• Requires a lot of specific investigations on items not common within the soil investigation and soil remediation (climate, plant growth) • Also, the remediation time for the process is significant	• Very suitable for contaminated sites where there are no time restrictions on remediation and no urgent land use. • Future genetic engineering will likely further improve the efficiency of the process	• Requires high quality of investigation data before starting the actual remediation. • The uncontrolled disposal or use of plants which are used for phytoremediation, poses a serious risk
Monitored Natural attenuation (MNA)	• Uses the natural processes occurring in the soil for remediation purposes. • Very low cost • Robust approach	• Requires a very long time. • The quality of project management and monitoring tends to suffer over this long time	• Only suitable for contaminated sites where there are no time restrictions • Very easy to adopt as part of a remediation scheme where COPR source areas are removed	• Requires a high-quality of investigation well in advance of implementing the process. • Restrictions on site- or groundwater usage are sometimes difficult to enforce over the long periods
In-situ thermal treatment	• A unique technology which can remediate Cr via in-situ desorption	• Very high costs needs. • Only feasible for limited amounts of material	• Suitable for target remediation of small, specific contaminations	• Requires a high quality of investigation, staff and equipment. • Restrictions on soil use after completion are significant

Figure 5: SWOT Analysis of Ex-situ (Excavation + Treatment method) Remediation Alternatives for Cr-contaminated sites

Remediation Technology Alternatives	SWOT Analysis			
	Strengths	**Weaknesses**	**Opportunities**	**Threats**
Excavation + Biological treatment / biopiles	• Require relatively little effort. • Low initial cost requirements	• Applicable to sites with very low Cr levels • Vital to plan ahead. • Take time and use space. • Ideal result implies delayed backfilling	• Removes the need to obtain reusable backfill soil from other parties. • Eliminates treatment in specialized installations elsewhere. • Can be a good choice as a last part of the remediation treatment train	• The biological treatment may completely fail, owing to toxic shocks from high Cr levels
Excavation + Treatment by soil washing	• Ability to treat most organic compounds as well as heavy metals	• Not suitable for soils with a fine content of more than 20 to 40 % by weight	• Relatively small in size, enabling mobile versions of the installation. • Can considerably cut costs, especially if the treated sand fraction is reused for backfilling the excavation	• Permanent soil washing installations may not be available or may be at a considerable distance from the remediation site
Excavation + Thermal treatment/ vitrification/ pyrometallurgical treatment/ pyrolysis	• Ability to effectively treat most organic compounds as well as certain heavy metals (like Cr) in silt and clay and mineral-rich peat-containing soils	• Expensive with high energy costs • Reuse of the treated soil may be limited because of loss of soil structure and organic matter, depending on the temperature of operation	• Relatively small in size, enabling mobile versions of the installation. • Can considerably cut costs, especially if the treated material is used as backfill	• Permanent installations may not be available or may be at a considerable distance from the remediation site
Excavation + Treatment by physical separation	• Ability to remove finer fractions of soil matrix which, generally, contains majority of chromium	• Physical separation by screens is not applicable to silt/clay-containing soils.	• Mechanical soil screens are particularly mobile and start to be effective already at relatively small volumes of contaminated material. • Can be good choice as a first part of remediation treatment train	• Having to operate in a containment (to reduce Cr suspension into air) will increase costs. • Treated material that still contains some level contaminants can remain controversial for reuse
Excavation + Secured landfill disposal (Civil engineering-based method)	• Ability of the landfill to store all types of contaminated soil directly	• Not a definitive solution as it consumes valuable land	• Highly established treatment option • Relatively simple operations • Can be good choice as a last part of remediation treatment train	• Not good for long-term sustainability perspective • High initial costs
Excavation + Relocation	• Drastic but working solution for the prevention of contaminant exposure. • The technical basics of the system are simple	• Relocation contaminates different regions. • The safety measures require indefinite control (/ monitoring)	• The site is valuable after contaminant relocation. • Can have benefits for biodiversity as the site	• Can generate desolate areas which will negatively affect communities
Excavation + Chemical Treatment	• Effective treatment method • Requires relatively low initial costs	• Requires specialized equipment, skills and planning. • Chemical costs can be high	• Can be used to either remove Cr (oxidation followed by leaching) or reduce its toxicity (by transforming Cr(VI) to Cr(III)) • If successful, then treated material can be backfilled at site	• Contaminant toxicity can rebound to pre-treatment levels. • Is highly specific to COPR characteristics at the site
Excavation + Solidification/ Stabilization (S/S)	• Proven technology • Applicable to wide range of contaminants, soils and waste types • Low maintenance costs	• Requires specialized equipment, skills and planning. • High initial costs	• If implemented correctly, then treated material can be backfilled at site. • The site is valuable post-remediation. • Can be good choice as a last part of remediation treatment train	• Treated material that still contains some level contaminants can remain controversial for reuse. • Might have some land use restrictions post-remediation

Figure 6: **SWOT Analysis of Civil Engineering-based Remediation Alternatives for Cr-contaminated sites**

Remediation Technology Alternatives	SWOT Analysis			
	Strengths	**Weaknesses**	**Opportunities**	**Threats**
Immobilization by in-situ grouting	• Ability to stop all the leaching. • Can be applied to an extensive range of contaminants by changing the grout material qualities	• Will always be limited to a specific group of sites locations • Only feasible for the remediation of limited amounts of soil	• Very suitable for target remediation of small, specific contaminations	• Requires a high quality of investigation, staff and equipment. • The assessment of the type of grout required is an essential step. • Restrictions on soil use after completion are significant
Vertical walls	• Ability to stop all the leaching from contaminants to the surrounding area. • Can be applied to an extensive range of contaminants and soil types	• Require indefinite control, management, and monitoring on the quality of the system	• If well-constructed and social needs are well-integrated into the design process, vertical wall can contribute to the restoration of an area	• Long-term functioning of the system • If no proper management, leakages from contamination likely • The increase in water level and associated pressure to the wall is a major threat
Capping layer (Soil cover, Membrane layer treatment, etc.)	• Ability to stop all infiltration of precipitation or weathering. • Prevents any exposure to contaminated material. • Can be applied to an contaminants, soil and waste types	• Require indefinite control, management, and monitoring on the quality of the system	• If well-constructed and social needs are well-integrated into the design process, vertical wall can contribute to the restoration of an area	• Long-term functioning of the system • If no proper quality management is carried out during installation and maintenance, damage of the capping layer is likely
No remedial actions + Land use restrictions	• Fast solution for uncontrolled direct exposure to all types of contaminants • Simple and have low maintenance costs	• The restrictions require indefinite control and monitoring	• Can have unexpected benefits (like natural attenuation of the site)	• Contamination and contaminant transport pathways still exist and needs addressing. • Can still have negative feedback from affect communities

[6] SWOT: CIVIL ENGINEERING-BASED METHODS

Remediation using Civil Engineering-Based Methods involves construction and engineering techniques applied directly to the site. They often involve the construction of physical barriers, caps, or other containment structures to immobilize, contain, and/or manage contaminants without necessarily directly treating the material.

As Civil Engineering-Based Methods focus on containing or managing contamination rather than directly treating the contaminants, they may provide a quicker solution but might not address the underlying issue comprehensively.

In summary, in-situ and ex-situ (either on-site or off-site) methods focus on treating contaminants, while civil engineering-based methods often involve construction and containment measures without direct treatment.

Figure 6 presents all the identified Strengths, Weaknesses, Opportunities, and Threats (SWOT) of all the Civil engineering-based remediation methods associated with Cr-contaminated sites.

The civil engineering-based methods of remediation address a short-term solution but fail the requirement of long-term sustainability. Additionally, Civil engineering-based methods may not be suitable for all types of contaminants, especially those contaminants that require direct treatment rather than containment.

TRANSCRIPT

ABSTRACT

The remediation of chromium (Cr) contaminated sites presents a complex challenge due to the hazardous nature of Cr compounds and their adverse impacts on human health and the environment. In addressing this pressing concern, the present study endeavors to contribute to the understanding of technology suitability for effective Cr-contaminated site remediation through a comprehensive Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis. Drawing upon an exhaustive review of the existing literature, this research first identifies and evaluates the strengths of various technologies commonly employed in Cr-contaminated site remediation. These strengths encompass the capacity of technologies to efficiently reduce Cr concentrations, promote sustainable remediation practices, and ensure minimal collateral damage to surrounding ecosystems. Furthermore, the analysis delves into the weaknesses of these technologies, highlighting potential limitations that may impede their optimal performance. The study then explores the opportunities that arise from implementing these technologies, including advancements in remediation processes, novel materials, and cutting-edge monitoring and assessment tools. Additionally, the research critically assesses the threats posed by the application of these technologies, encompassing potential economic, technical, and environmental challenges that may hinder their widespread adoption. By synthesizing these key findings, the study aims to provide valuable insights into the selection and deployment of appropriate remediation technologies tailored to Cr-contaminated sites. Furthermore, the SWOT analysis offers a structured framework for decision-makers, environmental practitioners, and policymakers to make informed choices concerning the most suitable technology options for site-specific circumstances. In conclusion, this research illuminates the diverse landscape of technologies available for Cr-contaminated site remediation, accentuating their respective strengths, weaknesses, opportunities, and threats. As such, this SWOT analysis serves as a vital resource in the ongoing efforts to remediate and restore Cr-contaminated sites, thereby safeguarding public health and the environment for future generations.

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