REVISTA ÁGUAS SUBTERRÂNEAS

Primary remediation techniques in contaminated aquifer areas – A review

Técnicas primárias de remediação em áreas de aquíferos contaminados – Uma Revisão

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ABSTRACT

This academic review brings important and recent information about remediation approaches specifically for contaminated aquifers, emphasizing their selection based on contaminant type and site-specific hydrogeological and environmental conditions. Groundwater pollution in urban environments results mainly from ineffective waste management and industrial or domestic activities, leading to persistent contaminants such as heavy metals and hydrocarbons. Here are presented some investigation steps, from Conceptual Site Modeling to remediation implementation, based on Brazilian and international references. It classifies contaminants, discusses risk assessment factors, and compares physical, chemical, and biological methods. Ultimately, it presents cost, efficiency, and implementation time data to support decision-making in aquifer remediation projects.

RESUMO

Esta revisão acadêmica apresenta informações recentes e relevantes sobre abordagens de remediação especificamente para aquíferos contaminados, enfatizando sua escolha com base no tipo de contaminante e nas condições hidrogeológicas e ambientais específicas do local de estudo. A poluição de águas subterrâneas em ambientes urbanos resulta principalmente do manejo inadequado de resíduos e de atividades industriais ou domésticas, levando a contaminantes persistentes, como metais pesados e hidrocarbonetos. São apresentados alguns passos de investigação, desde a Modelagem Conceitual do Local até a implementação da remediação, com base em referências brasileiras e internacionais. O estudo classifica os contaminantes, discute fatores de avaliação de risco e compara métodos físicos, químicos e biológicos. Por fim, apresenta dados de custo, eficiência e tempo de implementação para apoiar a tomada de decisão em projetos de remediação de aquíferos.

1. INTRODUCTION

Groundwater can be defined as the water stored below the water table, usually located inside pores and fractures of geologic formations in the saturated zone (Freeze; Cherry, 1979). In deeper subsurface environments, larger volumes of groundwater are stored below the superficial horizons, forming aquifer systems that can be connected to the hydrological cycle and contribute to the renewal of water resources (Freeze; Cherry, 1979). Of accessible freshwater available worldwide, 97% is represented by groundwater bodies available for human use. Considering it as a finite resource indispensable for the survival of living beings, its conservation is of fundamental importance (Gomes; Coutinho, 2007).

The importance of aquifer systems for sustaining life is indisputable. However, due to inadequate management and planning, contamination of underground water resources has become a widespread issue at the global scale (Baali, 2007; Hirata *et al.*, 2019; Burri *et al.*, 2019; Benamar *et al.*, 2019; El Meknassi *et al.*, 2020; Al-Hashimi *et al.*, 2021; Hamidi *et al.*, 2022). Case studies document contamination arising from diverse anthropogenic sources, such as landfill leachate impacts on aquifers in Algeria (Baali, 2007), while more recent studies reinforce that groundwater is vulnerable to a wide range of pollutants and often requires remediation to meet human, agricultural, and industrial water quality standards (Al-Hashimi *et al.*, 2021). As a result, these studies demonstrate that increasing anthropogenic pressures frequently exceed the natural self-purification capacity of groundwater systems.

According to Hirata *et al.* (2019), groundwater plays an important role in the Earth's hydrological cycle, particularly in maintaining freshwater reserves. The hydrogeological cycle consists of three main stages, recharge, subsurface flow, and discharge. Recharge is the most important process here, referring to the entry of water into the subsurface system, which can occur mainly from rainfall that infiltrates the soil instead of being lost through evaporation, transpiration, or surface runoff. Recharge is a result of the inflow of water from water bodies (rivers/lakes) that supply aquifers, or even artificially through direct water injection into boreholes.

Groundwater quality can be influenced by natural factors such as the chemical composition of rainwater, the geochemical characteristics of subsurface materials, the lithology of the aquifer, and other environmental conditions that affect the interactions between the water and the rocks. These natural processes determine the baseline chemical composition of groundwater. However, contamination refers to anthropogenic alterations of water quality, which can occur directly within the aquifer or in the surrounding soil in localized areas where the contamination source is well defined and identifiable, or in diffuse cases where the origin cannot be precisely determined (Madeira, 2010).

Industrial and economic expansion, since the last century, has stimulated patterns of mass production and consumption, leading to frequent and intense environmental problems. These impacts have created significant challenges and highlighted the urgent need to adopt new models of environmentally sustainable development (Santos *et al.*, 2008). Particularly, groundwater pollution worldwide is commonly a consequence of ineffective waste management, most often in shallower aquifers, located near domestic and industrial effluent discharge zones (Gomes; Coutinho, 2007). Millions of tons of hazardous waste are generated annually (SNIS, 2020), and waste disposal techniques are not always efficient. As a result, many sites are contaminated with heavy metals, organic compounds, or other hazardous substances that, when improperly discarded, permeate the soil and degrade groundwater quality, affecting associated ecosystems (Vera *et al.*, 2007). In some cases, pollutant compounds are unable to degrade naturally due to the absence of favorable environmental conditions, which allows them to persist for many years in groundwater and surrounding environments (Helene; Moreira, 2016).

Companies with the potential to generate environmental liabilities are developing and investing new technological strategies to improve waste management and, importantly, implementing new production routines that eliminate or minimize the use of potentially polluting resources (Oliveira *et al.*, 2025; Santos *et al.*, 2025). However, some industries still resist change, and they often degrade and contaminate manufacturing sites with chemical, toxic, and hazardous substances. In many cases, contamination persists long after the original source has stopped operating, requiring long-term monitoring and remediation actions to prevent risks to groundwater, ecosystems, and human health (Sillos *et al.*, 2025; Santos *et al.*, 2025).

Recent studies indicate that, despite advances in environmental regulation, the prevailing posture of many companies responsible for contaminated areas remains largely reactive rather than preventive. Remediation actions are often initiated only after regulatory enforcement, legal action, or strong institutional pressure, rather than as part of proactive environmental management. In several documented cases, companies delay or limit remediation efforts, resulting in persistent contamination, incomplete site recovery, and long-term environmental liabilities (Santos; Ribeiro, 2022; Sillos *et al.*, 2025). Consequently, the burden of managing these contaminated sites can shift to public authorities or remediation programs coordinated by environmental agencies, particularly when responsible parties fail to fully implement effective waste management and remediation measures (Sillos *et al.*, 2025).

In these circumstances, environmental investigation and remediation become essential steps of the environmental assessment and diagnostic process, particularly with regard to the protection and recovery of groundwater resources. Regulatory agencies and technical institutions in Brazil, the United States, and Europe recommend these procedures through internationally recognized institutional frameworks. In Brazil, *Companhia Ambiental do Estado de São Paulo* (CETESB) establishes a structured approach through the *Manual de Gerenciamento de Áreas Contaminadas* and Decision Directive nº 038/2017/C, which define investigation stages, risk assessment, and remediation measures with specific emphasis on contaminated aquifers. In Brazil, the *Conselho Nacional do Meio Ambiente* (CONAMA) provides guidelines through Resolution nº 420/2009, which sets soil quality criteria and investigation values directly linked to groundwater protection, while the *Agência Nacional de Águas e Saneamento Básico* (ANA) supports aquifer management through technical guidelines for groundwater protection and monitoring. In the United States, groundwater investigation and remediation practices are guided by the Environmental Protection Agency (EPA) under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) framework, notably through the Guidance for Conducting Remedial Investigations and Feasibility Studies (RI/FS) and the Risk Assessment Guidance for Superfund (RAGS). In addition, the ITRC (Interstate Technology & Regulatory Council) provides widely adopted technical guidance on groundwater remediation technologies, conceptual site models, and risk-based decision-making, serving as a key institutional reference for state and federal agencies. In Europe, groundwater remediation is supported by institutions such as the European Environment Agency (EEA), through reports on contaminated site management, and by regulatory frameworks like the Water Framework Directive (2000/60/EC) and the Groundwater Directive (2006/118/EC). These directives are operationalized at the national level by agencies such as the Environment Agency (EA, United Kingdom), with technical support from CL:AIRE (Contaminated Land: Applications in Real Environments), whose guidance documents promote sustainable, risk-based remediation and the management of groundwater-contaminated sites. Collectively, these guidelines emphasize site characterization, conceptual model development, risk-based decision-making, and the adoption of remediation strategies aimed at safeguarding groundwater quality and public health.

The application and effectiveness of these institutional frameworks have been further examined in scientific studies addressing remediation techniques, risk assessment methodologies, and groundwater protection strategies (Vera *et al.*, 2007; Silva *et al.*, 2022; Huang *et al.*, 2023). However, adopting new habits is usually a slow and complicated process, which causes environmental pollution to continue, harming the quality of ecosystems and putting the lives of those in direct contact with these environments at risk. In this context, environmental remediation techniques have become one of the main ways to treat contaminated environmental matrices, considering that these contaminations occur in different challenging ways, either due to the pollutant or to its relationship with the environment (Bertagi *et al.*, 2021).

The success of the project implementation aimed at remediating contaminated areas requires applying specific techniques capable of eliminating, isolating, or mitigating the contaminants until they reach acceptable and safe levels, thereby safeguarding the local population and the environment (Santos *et al.*, 2008). Therefore, this study aims to provide an academic overview of the primary techniques available for remediating contaminated aquifer areas through a literature review. It explores the application methods of these techniques and their respective characteristics, with the intention of facilitating the selection of the most suitable method based on the type of contaminant, and the location where it will be employed in the future.

2. METHODS

This review aimed to academically explore the topic "Primary remediation techniques in contaminated aquifer areas" by conducting a thorough search across various digital databases, including Google Scholar, Science Direct, Scielo, Uninove, USP and UFSC research repositories, Research Gate, Spring Nature and the Capes Journal Portal. These databases were selected to maximize the retrieval of studies aligned with the proposed theme. The search encompassed results published between 1979 and 2025. It utilized these specific keywords: "aquifer remediation", "remediation techniques", "domestic waste", "industrial waste", "bioremediation", "contaminated aquifer", "industry contamination", "biological remediation", "biogeochemistry", "geochemistry", "biostimulation", "soil and water contamination", "water contamination", "physical remediation", and "remediation of aquifers in the world". They were used both individually and in combined searches (e.g., "aquifer remediation AND bioremediation", "industrial waste AND groundwater contamination") to broaden the scope and capture studies addressing different remediation contexts and techniques.

Furthermore, a thorough examination of the references mentioned within the retrieved articles was done to identify any additional relevant studies in the field. About 200 articles and research publications related to the theme were initially selected, reflecting a targeted search aimed at capturing directly applicable studies presenting higher quality. Following a selection based on title and abstract relevance, the subsequent criteria were applied: remediation conducted in soils or waters, remediation performed in aquifers, methods considered feasible for practical implementation, and studies focusing on remediation methods. Consequently, the list was narrowed to 143 articles and research productions that investigated different remediation methods for different compounds in aquifers while providing pertinent and significant results. Materials that did not align with the study focus or failed to meet the quality criteria were excluded.

Ultimately, the findings were presented and organized into distinct topics, corresponding to each applicable remediation type. Additionally, a summary was included to succinctly outline the techniques. Overall, the employed research methodology ensured a systematic search for relevant studies within the field.

3. RESULTS AND DISCUSSION

a) Remediation Process

Remediation actions are essential in situations of groundwater contamination because they involve applying specialized technologies to immobilize or mitigate pollutants. These technologies can be applied individually or in combination, depending on the most suitable approach. Currently, there are options for conducting remediation either in specialized facilities (*ex situ*) or directly at the contaminated site (*in situ*). The preference is shifting towards *in situ* practices due to the potential risks and higher costs associated with *ex situ* approaches, which often require the removal of contaminated soil or water, endangering the local ecosystem (Eugris, 2008; Furtado, 2008; Santos *et al.*, 2008; Wang *et al.*, 2025; Shao *et al.*, 2025; Xie *et al.*, 2024).

Sequential actions are undertaken to optimize financial and technical resources in the management of areas where contaminants are or have been present, with information generated at each stage providing the technical basis for decision-making in subsequent phases. A critical component of this process is the execution of a detailed site investigation and the development of a Conceptual Site Model (CSM), which supports planning activities and guides the identification of appropriate remediation, control, and emergency measures when required.

In Brazil, these procedures are formally structured and recommended by environmental agencies through institutional guidelines and regulatory instruments issued by CETESB (*Companhia Ambiental do Estado de São Paulo*), the *Manual de Gerenciamento de Áreas Contaminadas* (CETESB, 2025) and a set of *Decisões de Diretoria* (DDs) that establish technical criteria and standardized procedures for the identification, investigation, risk assessment, intervention, remediation, monitoring, and closure of contaminated sites, with particular emphasis on soil and groundwater protection (Aguiar; Gabriel, 2014). Among these instruments, Decision Directive nº 038/2017/C (CETESB, 2017) defines the core procedures for the management of contaminated areas, while subsequent updates such as DD nº 106/2022/P (CETESB, 2022) and DD nº 056/2024 (CETESB, 2024) refine technical requirements and administrative workflows related to investigation stages, risk-based decision-making, intervention values, remediation objectives, and post-remediation monitoring. Together, these directives define a phased and integrated management framework aligned with international best practices.

At the federal level, complementary guidance is provided by CONAMA (2009), particularly through Resolution nº 420/2009, which establishes soil quality criteria and investigation values directly linked to groundwater protection. Similar stepwise and risk-based approaches are generally adopted in other Brazilian states under federal environmental regulations and the guidelines of state environmental agencies. At the international level, comparable frameworks are recommended by agencies such as the U.S. Environmental Protection Agency (EPA, 1988; EPA, 1989), through the CERCLA/Superfund program and associated guidance documents, and by technical institutions such as the Interstate Technology & Regulatory Council (ITRC, 2020). In Europe, these processes are aligned with the Water Framework Directive (2000/60/EC) and the Groundwater Directive (2006/118/EC) and are operationalized by national agencies such as the Environment Agency (United Kingdom) (LCRM, 2020), with technical support from CL:AIRE (2011).

It is important to highlight that, following the preliminary and confirmatory investigation stages, a detailed site investigation is carried out, and a Conceptual Site Model (CSM) is developed. This sequence is a previous step for selecting an appropriate remediation technique. According to Brazilian environmental guidelines (CONAMA Resolution No. 420/2009 and the National Program for the Recovery of Contaminated Areas – Brasil, 2020), the confirmatory investigation aims to verify the presence of contamination previously indicated in the preliminary assessment by collecting and analyzing environmental samples. Once contamination is confirmed, the detailed investigation seeks to define the spatial and vertical extent of the contamination, the affected environmental compartments (soil, groundwater, and air), and to identify potential receptors and exposure pathways. The CSM integrates hydrogeological characterization (with extent, depth, and connectivity of contaminated zones), contaminant distribution in the primary media, and relevant exposure pathways. Based on the CSM, the quantification of contaminant mass, concentration, remediation endpoints and performance targets are established, which in turn guide the design, implementation, and monitoring of the remediation program. These procedures are formally adopted and standardized within the Brazilian regulatory framework through the *Manual de Gerenciamento de Áreas Contaminadas* (CETESB, 2017, 2021, 2022, 2024, 2025), Decision Directive nº 038/2017/C and its subsequent updates (Decision Directives nº 106/2022/P and nº 056/2024), and CONAMA Resolution nº 420/2009.

b) Common types of contaminants

Groundwater is susceptible to contamination from a variety of anthropogenic sources, and understanding the main types of contaminants is essential for evaluating risks and selecting appropriate remediation strategies. Contaminants can be broadly grouped into industrial, domestic, and emerging classes, each with distinct characteristics, sources, and remediation challenges (Sidiropoulos, 2024; Islam; Quareshi, 2024; Mukherjee *et al.*, 2024).

Industrial contaminants originate mainly from manufacturing, mining, and petrochemical activities. These include inorganic substances such as heavy metals (lead, cadmium, chromium, mercury) and organic compounds, including Volatile Organic Compounds (VOCs), Polycyclic Aromatic Hydrocarbons (PAHs), and synthetic dyes. These contaminants are often highly persistent, toxic, and sometimes carcinogenic, with the potential to accumulate in soils and aquifers over decades (Mirlean *et al.*, 2005; Rana *et al.*, 2025; Mohammadikia *et al.*, 2025; Panigrahi; Santhoskumar, 2020). Heavy metals, in particular, are classified as Persistent Bioaccumulative Toxicants (PBTs) due to their low degradability, long-term persistence, and ability to mobilize under changing hydrogeochemical conditions (Abbasi *et al.*, 2021; Swarnkumar; Osborne, 2020; Liu *et al.*, 2021). Industrial effluents from sectors such as textile, metallurgical, and petrochemical operations can transport these substances through soils and heterogeneous aquifers, where preferential flow paths may amplify plume dispersion and complicate delineation and remediation (Slimene *et al.*, 2017; Mineo *et al.*, 2022; Shin *et al.*, 2022).

Domestic contaminants are primarily associated with inadequate sanitation, including insufficient access to treated drinking water and wastewater treatment infrastructure (Foster *et al.*, 2002; Suhogusoff *et al.*, 2013; Hirata *et al.*, 2015). In urban and peri-urban areas, septic systems, household chemicals, and pharmaceuticals represent diffuse sources of pollution, contributing to elevated levels of nutrients (particularly nitrogen in the form of nitrate), microbial pathogens, and emerging contaminants in groundwater (Yang *et al.*, 2017; Ruidas *et al.*, 2023; Ortúzar *et al.*, 2022). While these sources generally do not involve the high concentrations or diversity of industrial pollutants, their widespread and persistent nature poses long-term risks to water quality and complicates conventional remediation efforts.

Emerging contaminants include pharmaceutical residues, personal care products, veterinary products, industrial chemicals, and plasticizers. These substances are increasingly detected in both industrial and residential zones, often at low concentrations but with significant potential for bioaccumulation, persistence, and ecotoxicological effects (Lapworth *et al.*, 2012; Selak *et al.*, 2022; Ortúzar *et al.*, 2022; Li *et al.*, 2024). Unlike conventional pollutants, many emerging contaminants lack formal regulatory thresholds and are not fully removed by standard treatment methods, which highlights the need for proactive monitoring and tailored remediation strategies.

Collectively, these studies demonstrate that anthropogenic pressures, whether from industrial, domestic, or emerging sources, often exceed the natural self-purification capacity of aquifers, leading to persistent contamination that can impact human health, agricultural productivity, and ecosystem integrity. Understanding the type, source, and behavior of contaminants is therefore fundamental for selecting the most appropriate remediation technology and designing risk-based management strategies for groundwater protection.

Considering the diversity of contaminant types, sources, and behaviors described above, the selection of an appropriate groundwater remediation strategy requires a clear understanding of the available remediation technologies and their fundamental mechanisms of action. A wide range of techniques has been developed over the past decades, reflecting advances in hydrogeology, geochemistry, microbiology, and environmental engineering. In general, groundwater remediation methods can be grouped into five major categories: Physical Remediation, Chemical Remediation, Physicochemical Remediation, Biological Remediation (Bioremediation), and Thermal Remediation. Each group encompasses different techniques, with specific applications, advantages, and limitations depending on contaminant type, site conditions, and project objectives. Table 1 presents an overview of the main remediation techniques discussed in this paper, including their principal variations and definitions. This table is intentionally positioned at the beginning of the remediation section to provide a conceptual and organizational framework for the subsequent analyses. The comparative discussion of these techniques, addressing aspects such as efficiency, implementation time, operational duration, and costs, is developed in the following sections, where the reasons certain methods are currently preferred over traditionally applied techniques are examined.

In situ remediation techniques are often highlighted in the literature not only for their effectiveness in reducing contaminant concentrations, but also for practical advantages related to environmental impact and adaptability to site-specific conditions. Unlike *ex situ* methods that require excavation, transport, and above-ground treatment of contaminated media, in situ approaches treat contaminants directly at the site of contamination, thereby avoiding major surface disturbance, reducing risks associated with material handling and disposal, and minimizing disruption of the natural soil and aquifer structure (Zaib *et al.*, 2023). Furthermore, reviews of *in situ* groundwater and sediment bioremediation point out that these methods can have lower environmental impacts and reduced occupational risks compared with more invasive techniques, because they limit direct contact between workers and contaminated matrices and preserve site integrity (Majone *et al.*, 2014). These characteristics make *in situ* approaches adaptable to heterogeneous hydrogeological settings and a commonly applied option in contemporary remediation projects, complementing considerations of efficiency, cost, and implementation time.

c) How to evaluate contamination risk

In this context, groundwater contamination risk is associated with concentrations of certain compounds exceeding the permitted standards for the intended water uses. It is therefore essential to evaluate the hydrogeological characteristics and recharge dynamics of the aquifer under study. Factors such as soil type, land use, and human activities at the surface can influence infiltration and recharge rates, while processes occurring in the unsaturated and saturated zones control the vertical and horizontal transport of contaminants. In the unsaturated zone, processes such as adsorption, volatilization, biodegradation, and chemical transformation affect contaminant retention or mobility before reaching the groundwater table. Once in the saturated zone, advection, dispersion, diffusion, and sorption become dominant, controlling the distribution and movement of contaminants within the aquifer matrix. These mechanisms determine how fast and how far a contaminant plume can spread, depending on the hydraulic conductivity and heterogeneity of the geological formations involved (Hirata *et al.*, 2019; Baqer; Chen, 2022; Markale *et al.*, 2022; El-Aassar *et al.*, 2023). Additionally, the operation of multiple abstraction wells in densely populated or industrialized regions may induce downward flow gradients, facilitating the migration of contaminants from shallow layers to deeper aquifer zones (Khan *et al.*, 2016; Gailey, 2017; Hirata *et al.*, 2019; Qian *et al.*, 2020; Li *et al.*, 2022). These aspects highlight the importance of integrating recharge, pumping dynamics, and contaminant transport mechanisms into conceptual models for proper risk assessment and management of contaminated aquifers (Idelovitch; Michail, 1984).

Table 1 – Variation and definition of physical, chemical, physicochemical, biological, and thermal techniques mostly used in the remediation of contaminated soils and groundwater

Technique (ex situ/in situ)	***Variation***	***Definition***	***References***
Physical	Pump and Treat (P&T)	A traditional groundwater remediation method where contaminated water is extracted, treated above ground, and reinjected or discharged. It effectively contains contaminant plumes but is often slow and energy-intensive. As of 2025, P&T remains in use for hydraulic control or initial mass removal but is increasingly supplemented or replaced by *in situ* techniques like ISCO, ISCR, and bioremediation for long-term cleanup.	Gomaa *et al.*, 2021; Robinson *et al.*, 2025; Berglund; Cvetkovic,1995; Bortone *et al.*, 2020.
	Multi-phase Extraction (MPE / DPE)	MPE removes both groundwater and vapors to treat volatile or semi-volatile contaminants (e.g., hydrocarbons). It enhances removal rates by combining vacuum and pumping. Still widely applied in 2025, mostly for petroleum sites, though frequently integrated with bioventing or air sparging for improved efficiency.	Li *et al.*, 2025.
	Stabilization/ Solidification	This *ex situ* or *in situ* process immobilizes contaminants by mixing soils with binding agents (cement or pozzolans). It reduces leachability rather than removing pollutants. In 2025, it is still used mainly for metals and industrial sludges, though less favored for aquifer applications due to permeability reduction. Reactive barriers or ISCR are preferred alternatives.	Wei; Chi, 2023; Liao *et al.*, 2025.
	Hydraulic Barrier	Involves pumping wells or cutoff walls to control groundwater flow and isolate contamination. Common in complex plumes or near receptors. Still applied in 2024 for containment, but often replaced by reactive barriers or combined with natural attenuation for cost-effective, passive management.	Singh *et al.*, 2019; Ciampi *et al.*, 2024; Ebeling *et al.*, 2019.
	Excavation/Removal (soil)	Physical removal of contaminated soil followed by disposal or treatment. Highly effective for small, accessible sites but costly and disruptive. In 2024, it remained a standard emergency or hotspot remediation method, complemented by *in situ* soil treatment or thermal desorption for deeper contamination.	Huang *et al.*, 2023; Liu *et al.*, 2024.
	Air Sparging	Injects air into the saturated zone to volatilize and biologically degrade contaminants. Works best for VOCs in permeable aquifers. As of 2025, it remains widely used, often combined with SVE or bioventing. However, its effectiveness is limited in heterogeneous or low-permeability formations.	Liang *et al.*, 2012; Meng *et al.*, 2020; Newell *et al.*, 2021; Ben-Noah, 2025.
Chemical	Chemical Reduction (ISCR)	Reduces contaminants chemically (e.g., chlorinated solvents or metals) using reagents like zero-valent iron or sulfide donors. Highly effective for aquifers. Since the mid-2010s, ISCR has been increasingly adopted as a sustainable, long-term alternative to *Pump and Treat* and excavation.	Tratnyek *et al.*, 2014; Herrero *et al.*, 2018; Lasagas *et al.*, 2025.
	Chemical Oxidation (ISCO)	Applies oxidants (e.g., permanganate, persulfate, or ozone) directly into the subsurface to destroy organic contaminants. It acts fast and remained one of the most used *in situ* technologies in 2024, often coupled with bioremediation for polishing stages.	Xie *et al.*, 2020; Bolobajev *et al.*, 2016 Zhang *et al.*, 2016; Spina-Cruz *et al.*, 2019; McGachy *et al.*, 2024.
Physicochemical	Soil Vapor Extraction (SVE)	Applies vacuum to unsaturated soils to remove volatile contaminants as vapor. Efficient for petroleum hydrocarbons and solvents. In 2021, SVE was still common but usually part of combined systems (e.g., with air sparging or thermal treatment) for deeper contamination.	Liang *et al.*, 2012; Meng *et al.*, 2020; Newell *et al.*, 2021;
	Permeable Reactive Barrier (PRB)	An *in situ* passive system where groundwater flows through a reactive medium (e.g., zero-valent iron, activated carbon) that degrades or immobilizes contaminants. PRBs remain a leading technology in 2025 due to their low maintenance and sustainability, often replacing *Pump and Treat* systems.	Hidalgo *et al.*, 2025; Al-Hashimi *et al.*,2021;

Table 1 – Variation and definition of physical, chemical, physicochemical, biological, and thermal techniques mostly used in the remediation of contaminated soils and groundwater (continuation)

Technique (ex situ/in situ)	***Variation***	***Definition***	***References***
Thermal	Thermal Enhancements	Thermal remediation uses heat (steam injection, electrical resistance, or radiofrequency) to increase contaminant mobility and enhance removal rates, being particularly effective for DNAPLs and low-permeability zones. Despite technological advances and increasing integration with ISCO or SVE over the past decade, thermal methods remain less frequently prioritized due to their high-energy demand, operational complexity, and site-specific applicability.	Hiester; Schrenk, 2008; Sun *et al.*, 2021; Qin *et al.*, 2022; Luo *et al.*, 2025.
Biological	Bioremediation	Employs microorganisms to degrade organic contaminants *in situ* or *ex situ*. It is environmentally friendly and cost-effective. In 2025, bioremediation remains a cornerstone of aquifer restoration, increasingly enhanced with bioaugmentation and biostimulation techniques	Xie *et al.*, 2024; Zhang *et al.*, 2019; Xie *et al.*, 2020; Wu *et al.*, 2020; Yaqoubi *et al.*, 2025.
	Monitored Natural Atenuation (MNA)	Relies on natural processes (biodegradation, sorption, dilution) to reduce contaminant concentrations over time, with ongoing monitoring. Still widely accepted in 2025 for stable plumes, often following active remediation as a long-term management strategy.	Wei *et al.*, 2023; Widdowson *et al.*, 2008; Kringel *et al.*, 2023; Kirmizakis *et al.*, 2025
	Biopiles	*Ex situ* engineered piles that stimulate aerobic biodegradation of hydrocarbons in excavated soils through aeration and nutrient control. As of 2025, biopiles remain common for soil treatment but are gradually complemented by *in situ* bioremediation for reduced handling and cost.	Ostovar *et al.*, 2025; Baldan *et al.*, 2014; Yu *et al.*, 2021.

Another factor to be considered is that the contamination process usually occurs slowly, mainly in unconfined aquifers with a shallower water table or in systems with permeable confining layers. However, this assumption does not apply to dense non-aqueous phase liquids (DNAPLs), which can migrate rapidly through preferential flow paths and accumulate in deeper zones, posing long-term contamination risks (Booth *et al.*, 2019). As a result, even deep and confined aquifers can become vulnerable, and in these cases, remediation becomes particularly challenging, as some contaminants tend to form residual phases and persistent source zones that are difficult to remove by conventional methods. Thus, the risk of contamination depends not only on the contaminant load and aquifer vulnerability (Foster; Hirata, 1991) but also on the persistence and behavior of specific compounds and the hydraulic stresses imposed on the system. Understanding these interactions is therefore fundamental for defining appropriate investigation and remediation approaches. Figure 1 presents a flowchart designed to assess the potential risk of aquifer contamination based on site characteristics, local activities, and hydraulic conditions; the outcomes of this assessment inform the development of a prioritized list of polluting activities, required investigations, and appropriate monitoring measures.

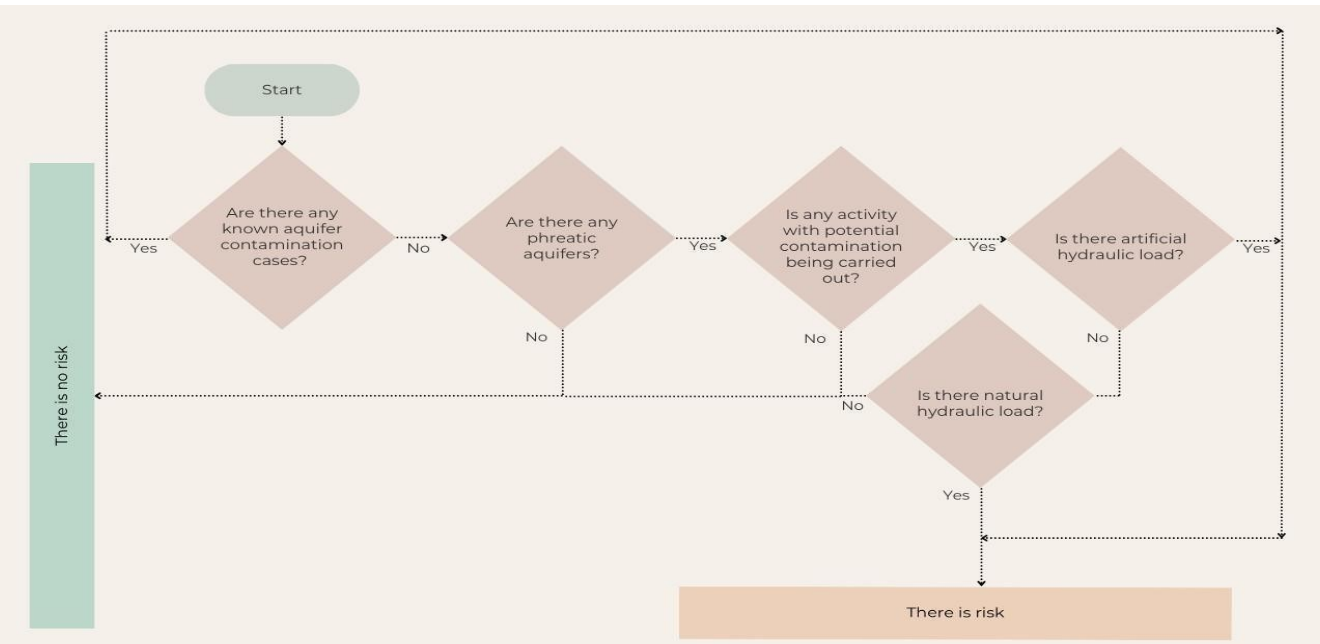

Figure 1. Flowchart that assists in basic identification of the risk of contamination of an aquifer.
Adapted from Foster e Hirata (1991).

d) How to select the most appropriate remediation method

For a contaminated area remediation project, specific techniques are required to eliminate, isolate, or mitigate contaminants until they reach acceptable and safe levels, protecting both the local population and the environment (Santos *et al*., 2008). Depending on the characteristics of the region and the type of contaminant, available methods can be applied individually or in combination, either *ex situ* or *in situ*. While many treatment technologies exist, those with faster action and a higher cost-benefit ratio are generally preferred (Alazaiza *et al*., 2022).

The efficiency of each method, however, depends on both the contaminant properties (e.g., chemical stability, solubility, volatility, persistence) and the site conditions (e.g., soil type, aquifer depth, hydrogeology, and presence of co- contaminants) (Alazaiza *et al*., 2022; Yu *et al*., 2024). For instance, bioremediation techniques tend to be highly efficient for biodegradable organic compounds such as petroleum hydrocarbons, but may be slower or less effective for persistent compounds like chlorinated solvents (Gomes; Coutinho, 2007; Bertolini *et al*., 2023; Mishra *et al*., 2024; Cano-López *et al*., 2024). Chemical oxidation or *in situ* chemical reduction methods can provide faster contaminant mass removal, but they may be costly and require careful control of reagent distribution to avoid incomplete treatment or secondary pollution (Liu *et al*., 2014; Sun *et al*., 2022; Wei *et al*., 2022). Physical methods, such as *pump- and-treat* or soil excavation, are generally effective in rapidly removing contaminants but can be resource-intensive and may generate secondary waste streams that need proper disposal (Truex *et al*., 2017; Carroll *et al*., 2024; Saqr *et al*., 2025).

In many complex scenarios, combined approaches have been shown to maximize remediation efficiency. Gomes and Coutinho (2007), for example, applied a parallel combination of techniques to tackle multiple contaminant classes simultaneously, illustrating the need for integrated solutions tailored to site-specific conditions. Furthermore, auxiliary techniques, such as soil vapor extraction or permeable reactive barriers, can enhance the performance of primary remediation methods by targeting residual contaminant fractions or controlling plume migration. For instance, Silva *et al*. (2022) demonstrated a parallel combination of electrokinetic remediation and a cork-based permeable reactive barrier for lead-contaminated soil and groundwater. Zhang *et al*. (2023) proposed a systematic "technology-mix" method based on contaminant distribution, integrating soil vapor extraction, chemical oxidation, and bioremediation to optimize site cleanup. Huang *et al*. (2023) highlighted that sequential or parallel combinations, like partial excavation followed by bioremediation, or soil amending plus advanced filtration for metals, are necessary to overcome site-specific complexity and maximize remediation efficiency. These examples highlight that combining multiple remediation strategies, adapted to local hydrogeology and contaminant characteristics, can significantly improve overall efficiency and effectiveness.

Overall, selecting the most appropriate groundwater remediation method requires careful consideration of contaminant characteristics, site-specific hydrogeological conditions, regulatory constraints, and project feasibility. In this study, Figure 2 presents a flowchart designed to support the preliminary identification of suitable aquifer remediation approaches primarily based on the maximum time available for method implementation. The flowchart distinguishes remediation strategies that are compatible with short, medium, or long-term intervention horizons, acknowledging that remediation timeframe is often a decisive constraint in contaminated-site management. Within each time category, additional conditioning factors, such as the contaminant origin and biodegradability, are considered to assess the technical feasibility of different methods, rather than to prioritize biologically based treatments. To complement this qualitative framework, Table 2 provides estimated ranges of implementation and operational costs for each remediation technique, compiled from available literature. Although some cost references are older due to the limited availability of recent peer-reviewed economic assessments, all values were standardized to Brazilian Reais (R$) using an average exchange rate of US$1 = R$5.38 (October 2025). It should be noted that the costs presented primarily reflect the estimated implementation and initial operation expenses, rather than the total expenditures over the full operational period; for example, Soil Vapor Extraction (SVE) may require additional costs over its 1–5 year operation depending on site conditions, contaminant concentrations, and operational efficiency. It is emphasized that actual costs, durations, and performance will depend strongly on site-specific parameters, including contaminant mass and chemistry, hydrogeological complexity, treatment footprint, logistical constraints, and regulatory requirements. See the reference column for case studies and cost reports used to compile these ranges.

An efficiency ranking is presented in Table 3. These values are estimative and may vary significantly depending on site-specific factors, including the type and concentration of contaminants, hydrogeological conditions, presence of co-contaminants, and local environmental constraints. The ranking is based on the expected overall efficiency under typical conditions; however, different methods perform optimally for specific contaminant types or environmental scenarios. For example, ISCO (*in situ* Chemical Oxidation) occupies the top rank due to its high mass removal efficiency in source zones, particularly for biodegradable organics and certain chlorinated solvents. Literature reports indicate that ISCO can achieve rapid removal of more than 70% of the contaminant mass under favorable conditions (Xie *et al*., 2020; Bolobajev *et al*., 2016; Zhang *et al*., 2016; Spina-Cruz; Maniero; Guimarães, 2019; Mcgachy *et al*., 2024). This emphasizes its effectiveness for quickly reducing contaminant concentrations in both industrial and domestic settings. ISCR (*in situ* Chemical Reduction) is ranked second because of its high effectiveness for chlorinated solvents when injection and contact conditions are adequate (Tratnyek *et al*., 2014; Herrero *et al*., 2018), though its applicability is more limited to industrial settings. PRBs (Permeable Reactive Barriers) rank third, as they provide good efficiency intercepting plumes, particularly for metals and ions, achieving >90% reduction under favorable hydrogeological conditions (Hidalgo *et al*., 2025; Al-Hashimi *et al*., 2021). Bioremediation approaches, although slower than chemical methods, are ranked fourth due to moderate to high efficiency for biodegradable organics when environmental conditions are suitable (Xie *et al*., 2024; Zhang *et al*., 2019). Similarly, Biopiles rank fifth for treatment of hydrocarbons and other biodegradable compounds in shallow soils, offering moderate efficiency but requiring longer treatment times (Ostovar *et al*., 2025). Air Sparging combined with Soil Vapor Extraction is ranked sixth because it is effective mainly for volatile organic compounds in the unsaturated zone. Its performance may be lower in saturated aquifers depending on hydrogeology (Liang *et al*., 2012; Newell *et al*., 2021). Multi-Phase Extraction ranks seventh, providing solid efficiency for LNAPL and VOC plumes when multiple phases are combined, but its complexity limits broader application (Li *et al*., 2025). *Pump and Treat* is ranked eighth, as it effectively controls plumes and extracts contaminants but is often slow to achieve final remediation goals, particularly in deep diffusion zones (Gomaa *et al*., 2021; Robinson *et al*., 2025). Excavation or Soil Removal, ranked ninth, acts as a physical method focused on source zones or contaminated soil. Its efficiency strongly depends on excavation depth and aquifer conditions (Huang *et al*., 2023). Thermal Enhancement is ranked tenth. Although this method is very efficient for degrading persistent organic contaminants and can accelerate both biodegradation and volatilization, its lower ranking in the overall efficiency table reflects practical and operational limitations rather than its intrinsic contaminant removal potential. The high cost, energy requirements, and complex logistics associated with large-scale implementation reduce its applicability across diverse sites, which explains why it scores lower in a comparative ranking despite its strong performance in contaminant degradation (Qin *et al*., 2022; Sun *et al*., 2021; Hiester; Schrenk, 2008). Hydraulic Barriers, ranked eleventh, provide good containment and flow control of plumes but do not remove contaminants, serving primarily to prevent migration (Singh *et al*., 2019; Ciampi *et al*., 2024; Ebeling *et al*., 2019). Stabilization or Solidification, ranked twelfth, immobilizes contaminants rather than removing them, showing good performance for metals and solid wastes (Wei; Chi, 2023; Liao *et al*., 2025). Finally, Monitored Natural Attenuation (MNA) ranks thirteenth, as its efficiency depends heavily on natural environmental conditions, usually requires long times, and removes contaminant mass slowly (Wei *et al*., 2023; Widdowson *et al*., 2008; Kringel; Wegner; Jelen, 2023).

Overall, this ranking emphasizes that efficiency is highly context-dependent: the best method varies with contaminant type, site conditions, and operational constraints. Selecting a remediation strategy requires integrating contaminant characteristics, hydrogeological conditions, and logistical considerations rather than relying solely on a generalized efficiency ranking.

4. CONCLUSION

Groundwater is an essential and finite resource, critical for human consumption, agriculture, and ecosystem survival. The increasing anthropogenic pressures from industrial, domestic, and agricultural activities have intensified the risk of groundwater contamination worldwide, introducing persistent organic compounds, heavy metals, emerging pollutants, and other hazardous substances into aquifers. These contaminants often persist due to limited natural attenuation, slow aquifer renewal rates, and hydrogeological complexities, underscoring the need for targeted remediation strategies.

This review highlights a variety of remediation approaches available until 2025, ranging from physical, chemical, physicochemical, biological, to thermal methods. *In situ* techniques, including ISCO, ISCR, bioremediation, PRBs, air sparging, and thermal enhancements, are increasingly favored due to their effectiveness, reduced environmental disturbance, and adaptability to site-specific conditions. Combined or hybrid approaches that integrate multiple technologies demonstrate enhanced efficiency, particularly in complex contamination scenarios involving multiple pollutants and heterogeneous aquifer systems.

The selection of an appropriate remediation strategy must consider contaminant properties, site hydrogeology, expected removal efficiency, timeframe, and cost. Decision-making tools, such as Conceptual Site Models, risk assessment frameworks, and cost-efficiency analyses, are fundamental for designing effective remediation programs. Despite technological advances, ongoing monitoring and management remain essential to ensure the long-term protection of groundwater quality and public health.

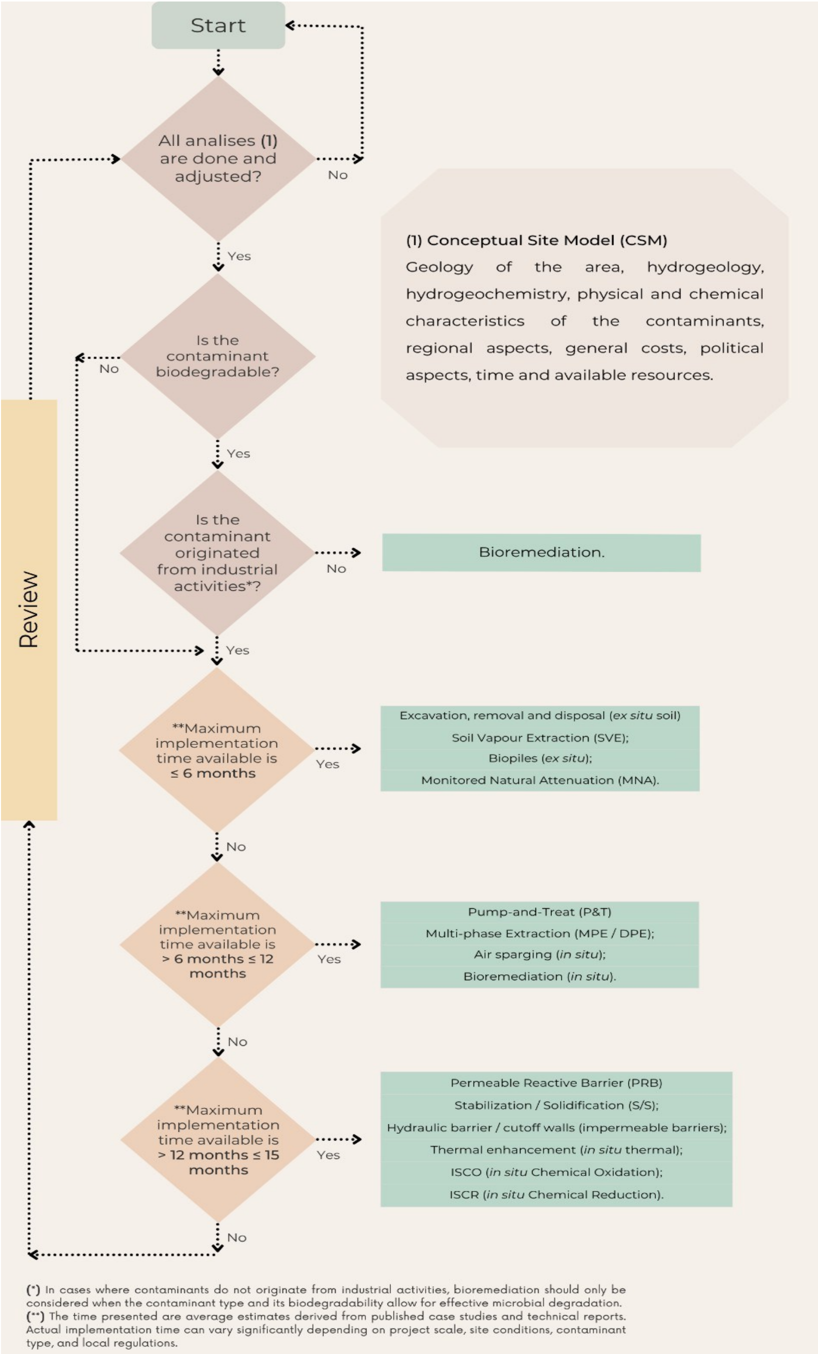

Figure 2. Flowchart for selecting the most appropriate aquifer remediation method based on the maximum time available for method implementation (planning and start-up phase). Adapted from EPA, 2000; Gavaskar *et al.*, 2000; EPA, 2001; Bayer *et al.*, 2005; EPA, 2005; Rosansky; Dindal, 2010; NAVFAC, 2012; Truex *et al.*, 2017; EPA, 2017; Fritz *et al.*, 2020; Falconi *et al.*, 2021; Orellana *et al.*, 2022; Yang *et al.*, 2023; Xie *et al.*, 2024; Krucon *et al.*, 2024; Song *et al.*, 2024; Yu *et al.*, 2024; FRTR, 2025a; Wiley; Leeson, 2025; FRTR, 2025b; FRTR, 2025c; CONAMA Resolution No. 420/2009; and the National Program for the Recovery of Contaminated Areas – Brasil, 2020.

Ultimately, the sustainable management and remediation of contaminated aquifers require a balance between scientific innovation, regulatory compliance, economic feasibility, and environmental stewardship. The adoption of advanced, integrated, and site-specific remediation strategies will continue to play a central role in safeguarding groundwater resources in 2025 and beyond.

Table 2 – Summary of average implementation time, operational duration, result onset, and cost estimates for groundwater remediation techniques. Costs were standardized to R$ using US$1 = R$5.38, October 2025

Group A – Implementation ≤ 6 months						
Method	**Implementation time**	**Operation duration**	**Time to measurable results**	**Estimated costs (USD / m³)**	**Estimated costs (BRL / m³)**	**Reference**
Excavation, removal and disposal (*ex-situ* soil)	1 – 3 months	Usually none	Immediate (once removed)	USD 15 -250/m³	R$ 81 - 1,345/m³	EPA, 2000.
Soil Vapour Extraction (SVE)	1 – 3 months	1 – 5 years	Weeks – months	USD 20 - 200/m³	R$ 108 - 1,076/m³	EPA, 2000.
Biopiles (ex situ)	2 – 6 months	Weeks – months	4 – 6 months typical (per batch)	USD 40 - 310/m³	R$ 215 - 1,668/m³	FRTR, 2025a; Orellana *et al.*, 2022.
Monitored Natural Attenuation (MNA)	1 – 6 months	5 – 30+ years	Months – years	USD 1 - 10/m³- yard	R$ 5 - 54 /m³-yard	EPA, 2017; Fritz *et al.*, 2020.
Group B – Implementation > 6 months and ≤ 12 months						
Method	**Implementation time**	**Operation duration**	**Time to measurable results**	**Estimated costs (USD / m³)**	**Estimated costs (BRL / m³)**	**Reference**
Pump-and-Treat (P&T)	3 – 6 months	5 – 30+ years	Months – years	USD 50 - 500/m³	R$ 269 - 2,690/m³	EPA, 2001; Truex *et al.*, 2017; *Song et al.*, 2024; Birnstingl; Wilson, 2024.
Multi-phase Extraction (MPE / DPE)	4 – 8 months	2 – 10 years	Weeks – months	USD 100 - 1,200/m³	R$ 538 - 6,456/m³	EPA, 2005; Krucon *et al.*, 2024.
Air sparging *(in situ)*	3 – 6 months	1 – 4 years	Weeks – months	USD 150 - 350/m³	R$ 807 - 1,883/m³	Wiley; Leeson 2025; Rosansky; Dindal, 2010.
Bioremediation *(in situ)*	3 – 12 months	1 – 5 years	Months – years	USD 50 - 310/m³	R$ 269 - 1,668/m³	Orellana *et al.*, 2022; Xie *et al.*, 2024; Madison *et al.*, 2023.
Group C – Implementation ≥ 12 months						
Method	**Implementation time**	**Operation duration**	**Time to measurable results**	**Estimated costs (USD / m³)**	**Estimated costs (BRL / m³)**	**Reference**
Permeable Reactive Barrier (PRB)	3 – 12 months	5 – 20+ years	Months – years	USD 50 - 500/m³	R$ 269 - 2,690/m³	Gavaskar *et al.*, 2000; NAVFAC, 2012.
Stabilization/ Solidification (S/S)	2 – 12 months	1 – 5 years	Immediate – months	USD 30 - 300/m³	R$ 161 - 1,614/m³	Hurst *et al.*, 2024; Yu *et al.*, 2024.
Hydraulicbarrier/cutoff walls (impermeable barriers)	3 – 15 months	Long-term	Immediate	USD 20 - 500/m²	R$ 108 - 2,690/m²	Bayer *et al.*, 2005.
Thermal enhancement (*in situ* thermal)	3 – 12 months	1 – 12 months	Days –weeks	USD 200 - 2,000/m³	R$ 1,076 – 10,760/m³	FRTR, 2025b; Yang *et al.*,
ISCO (*in situ* Chemical Oxidation)	Weeks - months	Months - Years	Days – weeks	USD 50 - 400/m³	R$ 269 - 2,152/m³	Falconi *et al.*, 2021; Rosansky; Dindal, 2010.
ISCR (*in situ* Chemical Reduction)	Weeks - months	Months - Years	Weeks – months	USD 50 - 300/m³	R$ 269 - 2,152/m³	FRTR, 2025c; Falconi *et al.*, 2021.

Table 3 – Estimated efficiency and suitability of common aquifer remediation methods for domestic and industrial contaminants. (-) indicates multiple use

Rank	Method	Estimated Efficiency	Relative Efficiency	Suitability	Type of contaminant	Reference
1º	ISCO (*in situ* Chemical Oxidation)	High	High mass removal efficiency in source zones, mostly for biodegradable organics; Literature reports > 70% rapid degradation.	Industrial and Domestic	Biodegradable organics Chlorinated solvents	Xie *et al*., 2020; Bolobajev *et al*., 2016; Zhang *et al*., 2016; Spina- Cruz *et al*., 2019; McGachy *et al*., 2024.
2º	ISCR (*in situ* Chemical Reduction)	High	Very effective for chlorinated solvents; High destruction rates if injection/contact is adequate.	Industrial	Chlorinated solvents	Tratnyek *et al*., 2014; Herrero *et al*., 2018.
3º	PRB (Permeable Reactive Barrier)	Medium	Good efficiency intercepting plumes; > 90% reduction for some ions/metals under suitable conditions.	Industrial and Domestic	Metals and íons	Hidalgo *et al*., 2025; Al-Hashimi *et al*., 2021.
4º	Bioremediation (*in situ*/enhanced)	High	Moderate to high efficiency for biodegradable contaminants; Slower than chemical methods, needs favorable conditions.	Industrial and Domestic	Biodegradable organics	Xie *et al*., 2024; Zhang *et al*., 2019; Xie *et al*., 2020; Wu *et al*., 2020.
5º	Biopiles	Medium	Good efficiency for biodegradable compounds in shallow soil/aquifers, mainly hydrocarbons; Moderate treatment time.	Industrial and Domestic	Biodegradable organics	Ostovar *et al*., 2025; Baldan *et al*., 2014; Yu *et al*., 2021.
6º	Air Sparging/ SVE (Soil Vapor Extraction)	Low-Medium	Good efficiency for volatile compounds in unsaturated zones; Performance in saturated aquifers depends on hydrogeology.	Industrial	VOCs	Liang *et al*., 2012; Meng *et al*., 2020; Newell *et al*., 2021.
7º	Multi-Phase Extraction (MPE/ DPE)	Medium-High	Effective for LNAPL plumes and VOCs when combined (water + vapor + NAPL); Solid efficiency but higher complexity.	Industrial	LNAPL and VOCs	Li *et al*., 2025.
8º	Pump-and-Treat	Medium-High	Effective for plume control and contaminant extraction; Often slow to reach final goals, lower efficiency in deep diffusion zones.	Industrial and Domestic	-	Gomaa *et al*., 2021; Robinson *et al*., 2025; Berglund; Cvetkovic, 1995; Bortone *et al*., 2020.
9º	Excavation/ Removal (soil)	Medium	As a physical method it mainly acts on source or associated soil; Efficiency depends on scope and aquifer depth.	Industrial and Domestic	-	Huang *et al*., 2023.
10º	Thermal Enhancement	Very High	High efficiency for persistent contaminants; Accelerates biodegradation and volatilization; High cost and logistics.	Industrial	Persistent organics	Qin *et al*., 2022; Sun *et al*., 2021; Hiester; Schrenk, 2008.
11º	Hydraulic Barrier	Medium	Good efficiency in plume containment and flow control; Does not remove contaminants but prevents migration.	Industrial and Domestic	-	Singh *et al*., 2019; Ciampi *et al*., 2024; Ebeling *et al*., 2019.
12º	Stabilization/ Solidification	Medium	Immobilizes contaminants, not necessarily removes them; Effective for metals and solid wastes.	Industrial	Metals	Wei; Chi, 2023; Liao *et al*., 2025.
13º	Monitored Natural Attenuation (MNA)	Low-Medium	Efficiency depends on natural conditions; Usually requires long times and slowly removes mass.	Industrial and Domestic	-	Wei *et al*., 2023; Widdowson *et al*., 2008; Kringel *et al*., 2023.

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