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In-Situ Remediation Strategies to Treat Polluted Water: A Review

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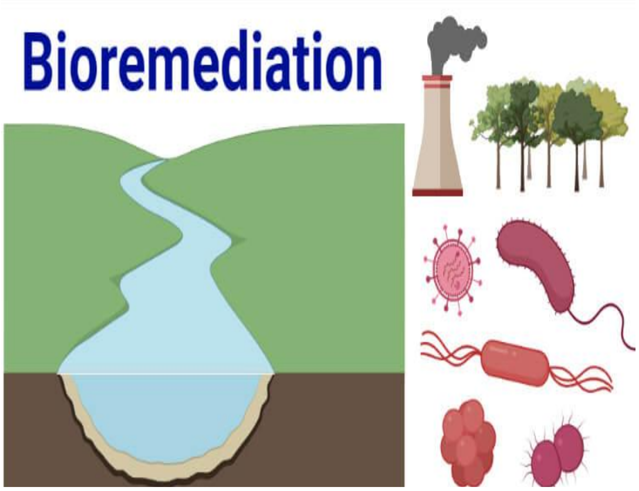
Abstract:

The contamination of water sources by diverse pollutants poses a substantial peril to both human well-being and environmental integrity. In this context, in-situ remediation strategies have emerged as noteworthy and cost-efficient methods to address water pollution sustainably. This review paper aims to furnish a comprehensive and holistic perspective on various in-situ remediation techniques deployed for treating polluted water. The paper extensively delves into the fundamental principles, benefits, limitations, and real-world instances of distinct in-situ remediation approaches. These encompass bioremediation, phytoremediation, chemical oxidation/reduction, and the utilization of permeable reactive barriers. The review emphasizes the pivotal significance of selecting the most suitable strategies, taking into account specific site conditions and the unique attributes of the pollutants. Additionally, the paper contemplates the challenges at hand and outlines prospective pathways for advancing in-situ remediation methods in the future.



Graphical Abstract

Keywords:*In-situ, bioremediation, heavy metals, wastewater, phytoremediation, oxidation*

Introduction:

Treating polluted water is of paramount importance due to its significant impact on human health, the environment, and sustainable development. Polluted water contains harmful contaminants such as chemicals, pathogens, heavy metals, and organic pollutants that can have far-reaching consequences. This brief overview will highlight the importance of treating polluted water, supported by references and citations. Polluted water is a major source of waterborne diseases such as cholera, typhoid, and diarrhea, which cause millions of deaths worldwide annually. According to the World Health Organization (WHO), nearly 2.2 billion people lack access to safe drinking water, exposing them to health risks Explanation of the concept of in-situ remediation and its advantages [1].Polluted water adversely affects aquatic ecosystems and biodiversity. It leads to the degradation of water bodies, disrupting aquatic life and causing the loss of valuable ecosystem services. Contaminated water can also infiltrate soil and groundwater, affecting land ecosystems and agricultural productivity [2]. Polluted water has economic implications, including increased healthcare costs, reduced labor productivity due to illness, and expenditures on water treatment. Moreover, it affects industries reliant on clean water sources, such as agriculture, tourism, and fisheries [3]. Access to clean and safe water is essential for achieving sustainable development goals, including those related to health, education, gender equality, and poverty eradication. Treating polluted water supports these goals by ensuring a healthier population and enabling socio-economic development [4].

In-situ techniques play a vital role in remediating heavy metal contamination in various environments, including soil and groundwater. These techniques involve treating the contaminated materials at their original location, rather than removing and treating them elsewhere. The advantages of in-situ techniques include minimal disturbance to the site, reduced cost, and the potential to treat large areas. Phytoremediation involves using plants to remove, stabilize, or reduce heavy metals from contaminated soil or water. Plants can accumulate heavy metals through processes like phytoextraction, where they take up metals from the soil and store them in their tissues. This technique is cost-effective and environmentally friendly [5].This technique involves adding amendments to the contaminated site to immobilize the heavy metals, reducing their mobility and bioavailability. Common amendments include lime, phosphate, and organic materials. The goal is to transform the heavy metals into less soluble and less toxic forms [6].Chemical fixation involves adding reagents to the contaminated site to induce chemical reactions that result in the precipitation or adsorption of heavy metals, rendering them less mobile and toxic. This technique is commonly used in treating heavy metals in soils and sediments [7].

Bioremediation

Bioremediation refers to the use of living organisms, such as bacteria, fungi, plants, and other microorganisms, to detoxify or eliminate pollutants from contaminated environments, with a focus on soil, water, and air. This process leverages the natural abilities of these organisms to degrade, transform, or immobilize various pollutants, making it a sustainable and environmentally friendly approach to pollution mitigation. Many microorganisms have the inherent capability to break down or transform a wide range of organic and inorganic pollutants present in water. These microorganisms use the pollutants as a source of energy or nutrients, resulting in the conversion of harmful compounds into less toxic substances. Bioremediation processes can occur in both aerobic (oxygen-rich) and anaerobic (oxygen-depleted) conditions. Aerobic processes involve the use of oxygen to break down pollutants, while anaerobic processes utilize other electron acceptors such as nitrate or sulfate. Both conditions support different microbial communities with varying abilities to degrade pollutants. Bioaugmentation involves introducing specific pollutant-degrading microorganisms into the contaminated water to enhance the natural biodegradation process. Biostimulation, on the other hand, involves providing nutrients or other growth-enhancing factors to stimulate the activity of indigenous microorganisms. Constructed wetlands are engineered systems that mimic natural wetland ecosystems. Plants, bacteria, and other microorganisms in these wetlands can remove pollutants through processes such as phytoextraction, rhizofiltration, and microbial degradation. This approach utilizes plants to remove, stabilize, or degrade pollutants in water. Plants can absorb contaminants through their roots and accumulate them in their tissues, effectively reducing the pollutant concentrations in the water. Biofiltration systems involve passing polluted water through a bed of specially selected microorganisms attached to a medium (such as sand or plastic beads). These microorganisms break down pollutants as the water passes through the bed. Biofilms are complex communities of microorganisms that adhere to surfaces. They can form in water bodies and play a role in breaking down pollutants by creating localized microenvironments that support specific microbial activities. Bioremediation offers various advantages, including its natural and sustainable nature, cost-effectiveness, and the potential for treating a wide range of pollutants. It can be applied on-site, reducing the need for transporting contaminated water to treatment facilities. Bioremediation's effectiveness can be influenced by factors such as environmental conditions (temperature, pH, oxygen levels), the presence of inhibitory substances, and the availability of suitable microorganisms. It may also be a relatively slower process compared to some chemical methods [2].

Microbial degradation is a process where microorganisms, such as bacteria and fungi, utilize pollutants as a source of energy and nutrients, leading to their transformation into less harmful compounds. Microbes possess enzymes that can break down complex pollutants into simpler molecules through metabolic pathways. Microbial degradation is a fundamental mechanism in bioremediation. For instance, hydrocarbons, pesticides, and organic contaminants can be degraded by specific microbial species. One well-known example is the degradation of hydrocarbons by oil-eating bacteria like *Pseudomonas* and*Alcanivorax* [8]. Adsorption is a process where pollutants are physically or chemically attracted to the surface of solid materials, such as soil particles, activated carbon, or clay minerals. The adsorption process can help immobilize pollutants, preventing their movement in water and facilitating their removal from the environment. Activated carbon is a common adsorbent used in water treatment due to its high surface area and strong adsorption capacity. It can effectively remove organic pollutants, heavy metals, and even certain chemicals [9]. Microorganisms can be employed to remediate heavy metal contamination through processes like bioremediation and bioaugmentation. Certain microbes can sequester, transform, or even detoxify heavy metals, reducing their impact on the environment [10]. Electrokinetic remediation involves applying an electric field to contaminated soil, sediment, or groundwater. This promotes the movement of heavy metals towards specific electrodes, allowing for their collection and removal [11].

These in-situ techniques offer diverse strategies to address heavy metal contamination effectively. However, the suitability of a specific technique depends on factors such as the type of heavy metal, site conditions, regulatory requirements, and cost-effectiveness. It's essential to conduct thorough site assessments and consider a combination of techniques for optimal remediation outcomes. For more detailed and up-to-date information, it's recommended to refer to scientific literature and research studies in the field of environmental remediation.

Phytoremediation:

Phytoremediation is a sustainable and environmentally friendly technique that uses plants to mitigate the presence of pollutants, including heavy metals, organic contaminants, and nutrients, from soil, water, or air. This natural process harnesses the inherent abilities of certain plant species to uptake, accumulate, and in some cases, detoxify pollutants through various mechanisms. Phytoextraction involves using plants to accumulate and store pollutants, primarily heavy metals, within their above-ground tissues. These plants, often referred to as hyperaccumulators, have the ability to selectively take up and translocate high concentrations of metals from the soil into their shoots. Once harvested, these plant parts can be removed from the site, effectively reducing the metal content in the soil [12]. Phytostabilization involves using plants to immobilize pollutants, particularly metals, in the soil by reducing their mobility and bioavailability. Certain plants have the ability to establish a strong root system that binds the contaminants in place, preventing their movement and subsequent entry into the food chain [13]. Rhizofiltration involves using plant roots to filter pollutants, such as heavy metals and nutrients, from water sources. Plants are grown hydroponically, and their roots act as a natural filter that captures and accumulates pollutants, effectively purifying the water [14]. Some plants have the ability to break down organic contaminants through phytodegradation, where the pollutants are transformed into less harmful compounds. Additionally, certain plants can take up volatile organic pollutants and release them into the atmosphere through a process called phytovolatilization [15].Phytoaccumulation involves the uptake and storage of pollutants in plant tissues, including both above-ground and below-ground parts. While not as selective as phytoextraction, this mechanism can still reduce pollutant concentrations in the environment [16].

Phytoremediation holds promise as a sustainable solution for addressing various types of pollution. The effectiveness of this technique depends on factors such as plant species selection, site conditions, and the specific pollutants present. Ongoing research continues to explore the potential of different plant species and their interactions with pollutants to enhance the efficiency of phytoremediation methods.

Plants play a crucial role in the uptake, accumulation, and degradation of pollutants, contributing to the process of phytoremediation. This natural approach utilizes plants to mitigate pollution by leveraging their unique biochemical and physiological capabilities. Certain plant species, known as hyperaccumulators, have evolved mechanisms to selectively take up and accumulate high concentrations of heavy metals from the soil. This process is driven by the plants' root systems and involves ion transporters that facilitate metal uptake [17]. Plants can absorb organic pollutants through their root systems and translocate them to various plant parts. This process can help reduce the concentration of pollutants in the surrounding environment [18]. Some plant species possess enzymes capable of breaking down organic pollutants, leading to their degradation into less harmful substances. This process occurs primarily in the plant's rhizosphere [19]. Certain plants can take up volatile organic pollutants and release them into the atmosphere through their leaves, effectively removing pollutants from the soil or water [20]. Plants influence the microbial communities in their rhizospheres, leading to increased microbial activity and enhanced pollutant degradation in the soil. Plant root exudates provide nutrients that support the growth of pollutant-degrading microorganisms [21]. Plants can be a link in the food chain, with pollutants accumulating in their tissues. This can lead to the biomagnification of pollutants as they move up the food chain, ultimately impacting higher trophic levels [22].

Chemical Oxidation/Reduction:

Chemical oxidation and reduction are in-situ remediation techniques commonly used to treat contaminated soil and groundwater. These techniques involve the introduction of reactive chemical agents into the subsurface to either oxidize or reduce contaminants, transforming them into less toxic or more easily extractable forms. Chemical oxidation is a technique that involves the addition of strong oxidizing agents to the contaminated site. These agents, such as hydrogen peroxide (H_2O_2), ozone (O_3), and potassium permanganate ($KMnO_4$), promote chemical reactions that break down organic contaminants into simpler and less toxic compounds. Chemical oxidation is particularly effective for treating organic pollutants like hydrocarbons and chlorinated solvents [23]. Chemical reduction involves the addition of reductants to the contaminated site, which facilitate the reduction of metal ions and other oxidized contaminants to less toxic or less mobile forms. Common reductants include zero-valent iron (ZVI), sodium dithionite (Na_2S2O_4), and organic carbon sources. This technique is effective for treating heavy metals, such as chromium and arsenic, as well as certain chlorinated solvents [24]. In some cases, a combination of chemical oxidation and reduction techniques, known as advanced oxidation-reduction processes (AOPs), is used for complex contamination scenarios. AOPs leverage the synergistic effects of both oxidation and reduction reactions to target a wider range of contaminants and achieve more comprehensive remediation outcomes [25].

Chemical oxidation and reduction techniques can be applied in-situ, reducing the need for excavation and off-site disposal. They are versatile and can target a wide range of contaminants. These techniques are often cost-effective and can be tailored to site-specific conditions. The success of these techniques depends on factors such as the type and concentration of contaminants, site characteristics, and the selection of appropriate chemical agents. There is a need for careful design, monitoring, and potential follow-up treatments to ensure the long-term effectiveness of these methods.

Hydrogen peroxide is a strong oxidizing agent used for in-situ chemical oxidation (ISCO). It generates hydroxyl radicals (OH) upon contact with contaminants, facilitating the oxidation of organic pollutants into less toxic compounds. It is effective for treating a wide range of contaminants, including hydrocarbons, chlorinated solvents, and pesticides [26]. KMnO4 is an oxidizing agent that releases oxygen when in contact with organic compounds. It is used for both in-situ chemical oxidation (ISCO) and in-situ chemical reduction (ISCR). $KMnO_4$ can oxidize a wide range of contaminants, including chlorinated solvents and certain pesticides [27]. Sodium persulfate is another oxidizing agent used in ISCO. It generates sulfate radicals (SO_4) that can oxidize organic pollutants. It is effective for treating petroleum hydrocarbons, chlorinated solvents, and other recalcitrant compounds [28]. Zero-valent iron is a reducing agent used for in-situ chemical reduction (ISCR). It donates electrons to contaminants, reducing them to less toxic forms. ZVI is commonly used for treating chlorinated solvents, heavy metals, and nitrates [29].

Permeable Reactive Barriers:

Permeable Reactive Barriers (PRBs) are innovative and passive groundwater remediation systems designed to treat contaminants as they flow through a reactive media-filled trench or wall. PRBs effectively target a wide range of pollutants, such as heavy metals, chlorinated solvents, and various organic compounds. These barriers take advantage of chemical reactions that occur between the contaminated groundwater and the reactive media, leading to contaminant immobilization, transformation, or removal. Thorough site characterization is essential to understand the hydrogeological conditions, contaminant distribution, and flow patterns of the groundwater. This information helps in determining the optimal location and design of the PRB. The selection of appropriate reactive media is crucial. Media can include zero-valent iron (ZVI) for reducing contaminants, activated carbon for adsorption, and various minerals for precipitation and immobilization. The choice depends on the contaminants to be treated and their reactivity with the media. The PRB's hydraulic design ensures that groundwater flows through the reactive media at an appropriate rate for effective contaminant treatment. Factors such as flow velocity, residence time, and hydraulic conductivity of the media are considered in this design. PRBs can be installed as trenches or walls perpendicular to groundwater flow. Trenches are commonly used for treating shallow groundwater, while walls are effective for intercepting plumes of contamination. Regular monitoring and maintenance are crucial to assess the PRB's performance over time. Monitoring wells are installed up- and downstream of the barrier to track contaminant concentrations and assess the need for media replacement [30].

PRBs operate passively, requiring minimal energy input once they are installed. This reduces long-term operational costs. Well-designed PRBs can provide long-term, sustainable contaminant treatment, reducing the need for continuous active interventions. PRBs can be tailored to treat a wide range of contaminants, making them versatile for different pollution scenarios. PRBs can be installed without major disruption to the site, minimizing the need for excavation or other invasive techniques. PRBs are effective for certain types of contaminants and may not be suitable for all pollutants. The complex geochemical interactions between the reactive media, groundwater, and contaminants can influence the effectiveness of PRBs. While PRBs require less maintenance than active systems, occasional media replacement or replenishment may be necessary. PRB design should be site-specific, considering hydrogeological conditions, contaminant characteristics, and treatment goals [31].

Reactive media used in permeable reactive barriers (PRBs) play a critical role in immobilizing or transforming pollutants through a combination of physical, chemical, and biological processes. The selection of appropriate reactive media depends on the type of contaminants and the desired remediation outcome. Reactive media such as activated carbon and certain clays have a high surface area and porosity, allowing them to adsorb contaminants onto their surfaces. This physical process involves contaminants adhering to the media, effectively reducing their mobility and concentration in the groundwater. Some reactive media introduce precipitation reactions that lead to the formation of insoluble compounds. This immobilizes contaminants by converting them into solid particles that are less mobile in groundwater. For instance, using reactive media that release metal ions can lead to the precipitation of metal hydroxides or sulfides. Certain reactive media have ion exchange capabilities, allowing them to replace harmful ions with less harmful ones. This process can immobilize contaminants by trapping them within the media's structure. Reactive media can promote redox (reduction-oxidation) reactions that transform contaminants into less toxic forms. For example, zero-valent iron (ZVI) is often used for in-situ chemical reduction, where it donates electrons to contaminants, reducing them into less harmful compounds. Some reactive media, such as hydrogen peroxide (H_2O_2) and potassium permanganate ($KMnO_4$), are used for in-situ chemical oxidation. These agents introduce powerful oxidants that react with organic pollutants, breaking them down into simpler, less toxic molecules. Certain reactive media provide a favorable environment for microbial activity, promoting biodegradation of organic contaminants. These media can support the growth of specific microorganisms that naturally degrade pollutants. Adjusting the pH of the groundwater using reactive media can impact contaminant solubility and speciation, promoting their transformation into less mobile or less toxic forms. The combination of various reactive media can create synergistic effects where multiple processes work together to immobilize or transform pollutants. For example, a combination of ZVI and organic carbon sources can enhance both reduction and biodegradation processes [32].

Selection and Challenges:

Selecting the most appropriate in-situ remediation strategy for a contaminated site requires a comprehensive understanding of site-specific conditions, contaminant characteristics, regulatory requirements, and the desired remediation goals. The selection process involves evaluating various factors to determine the most effective and efficient approach. The nature of the contaminants (e.g., organic compounds, heavy metals, nutrients) and their behavior (e.g., mobility, persistence) will significantly impact the choice of remediation strategy. Different contaminants may require different approaches for effective treatment. Understanding the extent and distribution of the contamination, as well as identifying the source(s) of contamination, is crucial for selecting the most appropriate remediation approach. The proximity of contamination sources to sensitive receptors also plays a role. The hydrogeological and geological conditions, including groundwater flow rates, direction, and subsurface structures, affect the transport and distribution of contaminants. Remediation strategies must consider how these conditions influence the movement of contaminants. Compliance with regulatory standards and guidelines is essential. Remediation strategies must align with local, state, and federal regulations, and the chosen approach should be approved by relevant authorities. Site accessibility, space availability, and physical constraints influence the feasibility of different remediation techniques. Some strategies may be more suitable for confined spaces, while others may require larger areas. Understanding the interests and concerns of stakeholders, including property owners, local communities, and government agencies, is important. The chosen remediation approach should be compatible with the intended land use after remediation. The technical feasibility of implementing a remediation strategy is a critical factor. The availability of required resources, expertise, and equipment can impact the selection. Some techniques may be complex and require specialized knowledge. The desired timeframe for achieving remediation goals influences strategy selection. Short-term goals may require more aggressive approaches, while long-term goals could involve gradual, passive methods. Budget constraints play a significant role in strategy selection. Remediation costs include not only the initial implementation but also ongoing monitoring and maintenance. The potential impact of the chosen strategy on the surrounding environment, including ecosystems and water resources, must be considered. Remediation should aim to minimize negative impacts. A thorough risk assessment helps identify potential risks associated with different remediation strategies. Strategies should be selected that effectively mitigate risks to human health and the environment. The long-term effectiveness and sustainability of the chosen strategy are crucial. Some strategies may yield quick results, but the sustainability of those results over time is equally important [22].

In-situ remediation offers numerous benefits, but it also comes with its own set of challenges that need to be carefully considered for successful implementation. Some of the key challenges associated with in-situ remediation include monitoring, long-term effectiveness, and maintaining site conditions. Monitoring the effectiveness of in-situ remediation can be challenging due to the complex nature of subsurface environments. Factors like heterogeneous geology, groundwater flow, and contaminant behavior make it difficult to predict and track the movement of contaminants and treatment agents. Continuous real-time monitoring of subsurface conditions and contaminant concentrations is essential for evaluating the progress of remediation efforts. However, setting up and maintaining monitoring systems can be technically demanding and costly. Variability in groundwater flow rates, contaminant concentrations, and other site-specific factors can lead to spatial and temporal variations in treatment efficiency. Monitoring must account for these variations to ensure accurate assessment [33]. Ensuring the long-term effectiveness of in-situ remediation techniques is crucial. Contaminants may persist or re-emerge over time if not properly managed, leading to the need for continued monitoring and maintenance. Some in-situ remediation methods rely on natural attenuation processes that may take years or even decades to achieve desired outcomes. Demonstrating the long-term effectiveness of these passive techniques can be challenging [34]. In some cases, in-situ remediation relies on microbial activity for degradation or immobilization of contaminants. Maintaining favorable conditions for these microorganisms (e.g., nutrient availability, pH) can be challenging, especially in changing environments. The introduction of reactive agents or amendments can lead to changes in subsurface geochemistry that may affect treatment efficiency. Monitoring and adjusting these conditions may be necessary to maintain treatment effectiveness [35]. In-situ remediation techniques may require regulatory approval before implementation. Ensuring that the chosen technique aligns with local regulations and standards can be challenging. Involving stakeholders, such as property owners and local communities, in the decision-making process can be complex. Balancing technical requirements with stakeholder concerns is important for successful remediation [36].

Future Prospects:

In-situ remediation techniques are continually evolving to address environmental contamination's complexities and improve treatment efficiency, cost-effectiveness, and sustainability. Several emerging trends and advancements in in-situ remediation are shaping the field. Emerging advancements in sensor technologies, remote sensing, and data analytics enable real-time monitoring of subsurface conditions. Wireless sensor networks, drones, and satellite imagery provide valuable insights into contaminant behavior, groundwater flow, and treatment efficiency. This data-driven approach enhances decision-making and allows for adaptive management of remediation efforts. Nanoscale materials, such as nanoparticles, are being explored for their potential to enhance contaminant removal and transformation. Nanoremediation involves introducing engineered nanoparticles that can interact with contaminants at the molecular level, leading to more efficient degradation or immobilization. Advances in molecular biology and genetic engineering are being applied to enhance bioremediation processes. Engineered microorganisms with enhanced degradation capabilities are being developed to target specific contaminants. Bioaugmentation and biostimulation techniques are benefiting from these advancements. Electrochemical and electrokinetic methods are gaining traction for in-situ remediation. Electrochemical techniques involve the application of electrical currents to stimulate redox reactions, while electrokinetic methods use electrical fields to drive contaminant migration.

These approaches are effective for both organic and inorganic contaminants. Phytoremediation techniques are being enhanced through genetic modification and plant-microbe interactions. Plants are being engineered to express enzymes that enhance pollutant degradation. Additionally, specific microorganisms are being introduced to plant root zones to boost rhizoremediation capabilities. Microbial fuel cells (MFCs) are being explored as a remediation approach that simultaneously generates electricity. MFCs use microbial metabolism to break down contaminants while producing an electric current. This innovative approach combines bioremediation with renewable energy generation. Emerging trends involve combining multiple remediation techniques for synergistic effects. For example, combining in-situ chemical oxidation with bioremediation can target a wider range of contaminants and optimize treatment outcomes. Environmental sustainability is a growing consideration in remediation strategies. Green and sustainable remediation aims to minimize the environmental footprint of remediation activities, incorporating energy efficiency, low-impact technologies, and reduced carbon emissions. Integration of geospatial data, subsurface modeling, and machine learning techniques enables the development of predictive models for contaminant transport and remediation outcomes. These models assist in designing effective remediation strategies. Advances in passive remediation methods, such as enhanced natural attenuation, use of permeable reactive barriers, and phytotechnologies, are gaining prominence due to their long-term sustainability and minimal operational costs [37].

Conclusion:

In-situ remediation is crucial to treating contaminated water. These methods help remove groundwater and soil contaminants efficiently and sustainably. In-situ technologies reduce costs and indirect environmental consequences by treating pollutants in their natural habitat. In-situ remediation is important because it may adjust techniques to heavy metals, organic compounds, and new contaminants. Different contaminants need different treatment methods, and in-situ procedures provide for versatility. Additionally, in-situ solutions minimise energy consumption and carbon emissions associated with excavation-based procedures, supporting the increased focus on green and sustainable restoration. However, site-specific circumstances, pollutant behaviour, and local restrictions must be understood for effective in-situ treatment. Every site has distinct hydrogeological, geological, and pollutant features that must be addressed when choosing and executing remediation methods. This sector requires ongoing study and innovation to enhance in-situ cleanup tactics, technology, and efficiency. In conclusion, in-situ remediation is essential to fighting water contamination. Their versatility, cost-effectiveness, and low environmental impact make them essential for polluted site restoration. Site-specific considerations and continuous research and cooperation among environmental experts, academics, regulators, and stakeholders will drive breakthroughs in this sector, assuring the effective and sustainable remediation of dirty water for centuries.

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