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Review

AI-assisted systematic review on remediation of contaminated soils with PAHs and heavy metals

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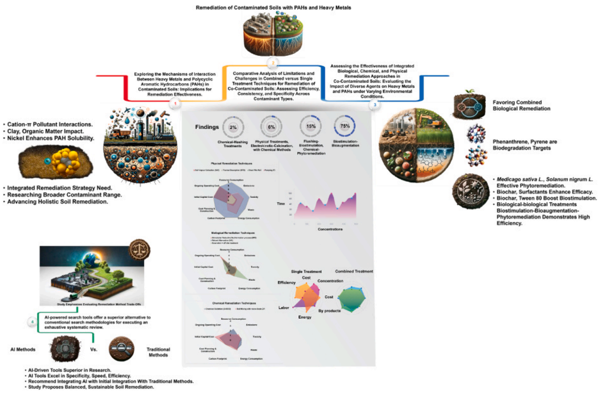
HIGHLIGHTS

- Remediation approaches mainly focused on the removal of phenanthrene, pyrene, Pb, Cd.
- Contaminant interplay skews treatment impact, calls for combined-resilient strategies.
- Long-term study and phytoremediation cleanup are key to successful soil remediation.
- AI search methods boosts research accuracy and speed over conventional methods.

GRAPHICAL ABSTRACT



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ABSTRACT

This systematic review addresses soil contamination by crude oil, a pressing global environmental issue, by exploring effective treatment strategies for sites co-contaminated with heavy metals and polycyclic aromatic hydrocarbons (PAHs). Our study aims to answer pivotal research questions: (1) What are the interaction mechanisms between heavy metals and PAHs in contaminated soils, and how do these affect the efficacy of different remediation methods? (2) What are the challenges and limitations of combined remediation techniques for co-contaminated soils compared to single-treatment methods in terms of efficiency, stability, and specificity? (3) How do various factors influence the effectiveness of biological, chemical, and physical remediation methods, both individually and combined, in co-contaminated soils, and what role do specific agents play in the degradation, immobilization, or removal of heavy metals and PAHs under diverse environmental conditions? (4) Do AI-powered search tools offer a superior alternative to conventional search methodologies for executing an exhaustive systematic review?

Utilizing big-data analytics and AI tools such as Litmaps.co, ResearchRabbit, and MAXQDA, this study conducts a thorough analysis of remediation techniques for soils co-contaminated with heavy metals and PAHs. It

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emphasizes the significance of cation-π interactions and soil composition in dictating the solubility and behavior of these pollutants. The study pays particular attention to the interplay between heavy metals and PAH solubility, as well as the impact of soil properties like clay type and organic matter on heavy metal adsorption, which results in nonlinear sorption patterns. The research identifies a growing trend towards employing combined remediation techniques, especially biological strategies like biostimulation-bioaugmentation, noting their effectiveness in laboratory settings, albeit with potentially higher costs in field applications. Plants such as *Medicago sativa L.* and *Solanum nigrum L.* are highlighted for their effectiveness in phytoremediation, working synergistically with beneficial microbes to decompose contaminants. Furthermore, the study illustrates that the incorporation of biochar and surfactants, along with chelating agents like EDTA, can significantly enhance treatment efficiency. However, the research acknowledges that varying environmental conditions necessitate site-specific adaptations in remediation strategies. Life Cycle Assessment (LCA) findings indicate that while high-energy methods like Steam Enhanced Extraction and Thermal Resistivity - ERH are effective, they also entail substantial environmental and financial costs. Conversely, Natural Attenuation, despite being a low-impact and cost-effective option, may require prolonged monitoring.

The study advocates for an integrative approach to soil remediation, one that harmoniously balances environmental sustainability, cost-effectiveness, and the specific requirements of contaminated sites. It underscores the necessity of a holistic strategy that combines various remediation methods, tailored to meet both regulatory compliance and the long-term sustainability of decontamination efforts.

1. Literature review

1.1. Advanced technologies for soil remediation: factors influencing remediation approaches

The domain of soil remediation encompasses a diverse range of strategies specifically formulated to eliminate contamination from heavy metals and petroleum hydrocarbons, including polycyclic aromatic hydrocarbons (PAHs). These strategies are classified into three principal types: physical, biological, and chemical, each distinguished by its specialized techniques and purposes. Despite considerable advancements in these strategies, their efficacy is influenced by multiple elements. Factors such as the complex interactions between PAHs, heavy metals, and other pollutants, the levels of contamination present, the duration required for thorough decontamination, and the economic implications associated with the remediation method chosen, all play pivotal roles in determining the success of soil remediation efforts [1–4].

1.1.1. Physical remediation technologies

Physical remediation techniques are prized for their swift results, often surpassing biological and chemical methods in speed, crucial for immediate risk reduction [4–7]. These methods effectively handle various contaminants and are particularly noted for directly extracting pollutants, reducing risks linked with in-situ pollutant retention common in biological approaches. Adaptability is another strength, with options for both in situ (on-site) and *ex situ* (off-site) applications, which can be tailored according to the specific needs and constraints of the site. In certain scenarios, physical remediation can also facilitate the recovery of valuable materials, such as metals, from contaminated soils. Furthermore, these techniques can effectively complement chemical or biological methods, forming part of an integrated, multi-step remediation strategy. Physical remediation encompasses a range of direct and tangible methods aimed at immobilizing or extracting contaminants from soil. These techniques have proven effective in removing petroleum hydrocarbons and heavy metals from contaminated soils. Essential methods encompass physical sorting techniques, electrokinetic remediation, soil excavation, soil washing, soil flushing, supercritical fluid extraction, soil vapor extraction, and air sparging (Fig. 1) [4,8,9]. Enhancing contaminant removal efficiency often involves using solvents alongside these physical methods. Solvents help by increasing the solubility of contaminants, thus facilitating more effective extraction [4,8,9]. Physical sorting techniques utilize particle size differences for effective contaminant separation. For example, soil washing is an effective method where organic compounds, often binding to finer particles, are treated with a liquid like a solvent or surfactant. This process promotes the adherence of contaminants to fine-grained soil (clay) and their subsequent transfer to coarser grains (sand), making it particularly adept at removing high molecular weight PAHs [10,11]. Electrokinetic treatment, another notable method, generates an electrical flow within contaminated soil, enabling the movement of contaminants towards subsurface electrodes. While effective, its standalone use for PAH removal has shown variable outcomes. Enhancing its efficacy often involves integration with other techniques, such as ultrasound stimulation, iron-based oxidation, and the addition of surfactants for better PAH removal [12]. Soil excavation, a more traditional approach, entails physically removing contaminated soil for either onsite treatment or transport to a different location for processing. Despite its widespread use, this method can sometimes be less efficient and may even lead to secondary contamination, necessitating specialized storage [13,14]. Soil washing is a process that uses aqueous solutions, including surfactants, chelators, or leaching agents, to extract contaminants according to particle size [15]. Similarly, soil flushing merges physical and chemical extraction methods, employing water, surfactants, acids, and chelating agents to mobilize contaminants into a liquid form for removal [16,17]. Supercritical fluid extraction stands out for its effectiveness in removing both heavy metals and PAHs from soil. This technique utilizes supercritical fluids as solvents under elevated temperatures and pressures to achieve high contaminant removal efficacy [5–7]. Soil vapor extraction (SVE) uses vacuum pressure for in-situ contaminant removal, effective for low molecular weight PAHs but less so for heavier PAHs [3,18]. Air sparging injects air to strip soil contaminants, aiding in biodegradation [19]. Thermal treatment's effectiveness varies with temperature; it's often combined with other methods due to its potential to alter soil properties [20–24]. These methods offer varied solutions for soil contamination, each tailored to specific contaminant types and site conditions.

Conversely, physical remediation methods, particularly those implemented off-site, can entail substantial costs. This is due to the need for specialized equipment, high energy consumption in processes like thermal treatments, and potential soil transport costs in *ex situ* applications. Physical methods such as excavation and transportation may pose risks of secondary contamination if not meticulously executed [23,25]. Physical remediation methods, especially those conducted off-site, can incur significant costs due to the need for specialized equipment, high energy usage in thermal treatments, and soil transportation for *ex situ* applications [28,30]. Even though Excavation and transportation, common physical methods, risk secondary contamination if not carefully managed. These methods can also disrupt the remediation site, potentially damaging ecosystems, infrastructure, or landscapes, and may be less effective for contaminants that are deeply buried or widely dispersed [13,14]. Soil washing, while frequently employed, can alter soil structure, and subsequently impact its fertility and ability to support vegetation. Thermal treatments in physical remediation, known for their high energy use, lead to considerable operational costs and carbon emissions. A significant limitation of these methods is their tendency to concentrate, rather than fully remove, contaminants, often necessitating further treatment or disposal. Public resistance, particularly to disruptive practices like excavation, presents challenges, exemplified by the NIMBY ("Not in my backyard") syndrome [26]. Moreover, questions about the scalability and economic feasibility of these methods for extensive clean-up operations remain. Post-remediation changes in soil's physical and chemical properties, such as compaction or organic matter reduction, may also restrict its future utility [26].

Physical remediation methods present a versatile array of solutions for soil contamination, effective in removing substances like petroleum hydrocarbons and heavy metals. These methods offer quick response, precise control, and adaptability for both in situ and *ex situ* applications. Techniques such as electrokinetic remediation, soil washing, soil flushing, air sparging, and thermal treatment cater to various contamination scenarios, each with its specific strengths. While powerful, these techniques have limitations, including variable efficiency based on soil composition, contaminant concentration, and co-contaminants presence. Some, like thermal treatment, might alter soil properties, leading to secondary impacts. Selecting the most suitable method requires balancing effectiveness with long-term soil health and ecosystem impact. Often, combining physical methods with chemical or biological strategies provides a comprehensive solution. Despite challenges, physical remediation is crucial in environmental cleanup, with ongoing research aimed at enhancing efficiency, cost-effectiveness, and environmental sustainability.

1.1.2. Biological remediation technologies

Biological remediation employs natural processes to convert hazardous substances into less harmful forms, such as CO_2, water, and inorganic salts [27,28]. This method, encompassing bioremediation, phytoremediation, and vermicomposting, offers environmental, social, and economic benefits. Bioremediation uses bacteria and fungi to clean up contaminated soils sustainably. Phytoremediation leverages plant-microbe interactions, while vermicomposting utilizes earthworms, which enhance soil properties and boost microbial activity for

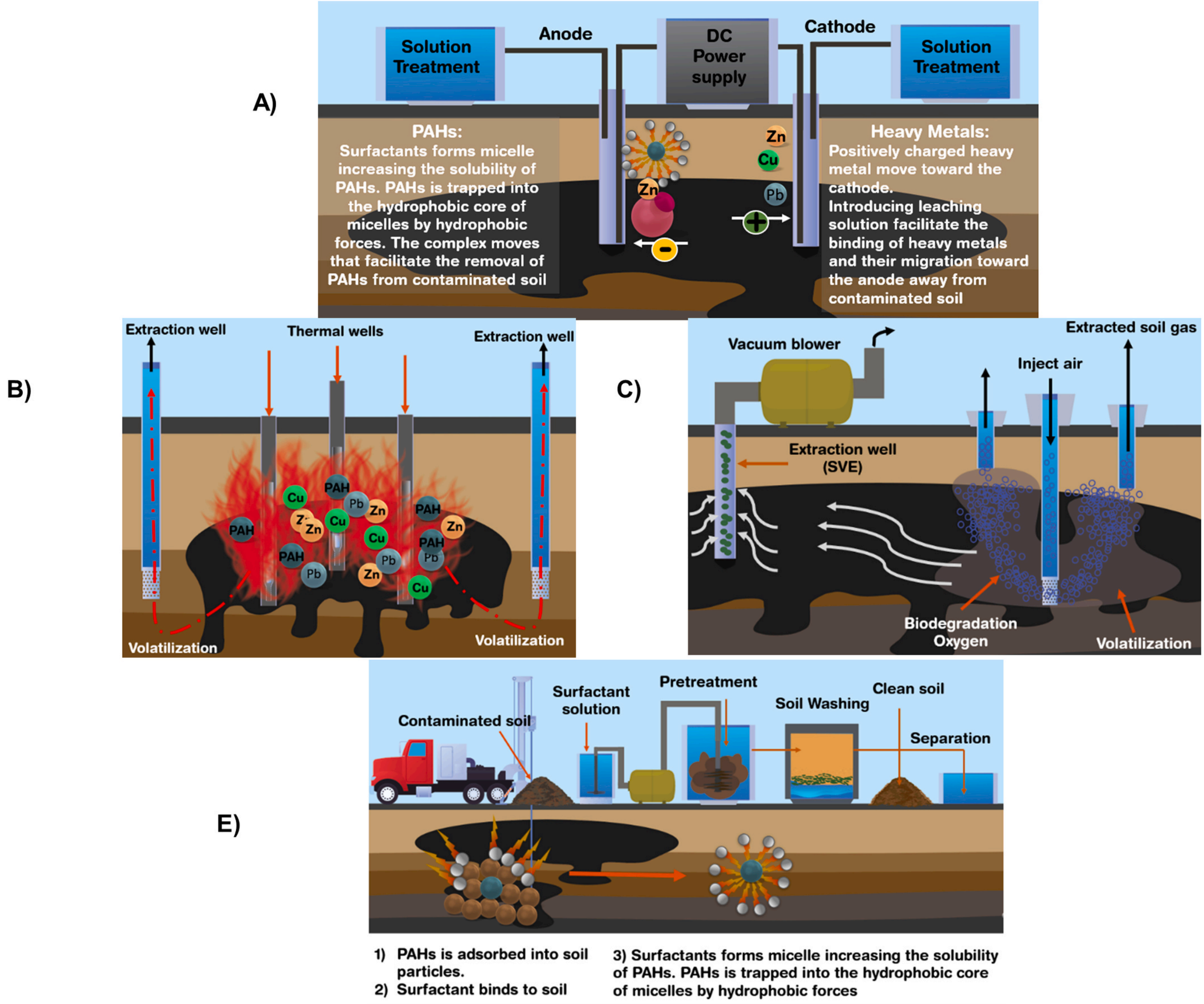

Fig. 1. Physical Remediation. (A) Electrokinetic: Applying low voltage direct current in the soil matrix. (B) Thermal: Applying electrical resistance heating in the soil, (C) Soil vapor extraction: Injecting gas flow using vacuum blower and contaminated soil vapor is extracted to be treated at the soil surface. (D) Air Sparging Injecting air in contaminated qualifier and contaminants are extracted by vacuum extracted wells. (E) Soil Washing: Removing contaminated soil to be treated at the surface by mechanical scrubbing and washing.

more effective contaminant degradation [29]. Eco-friendly bioremediation offers a cost-effective alternative for soil decontamination, often requiring fewer resources and equipment than chemical or physical methods. Its suitability for in situ application is a significant advantage, eliminating the need for excavation and transportation of contaminated soil, thus reducing both carbon emissions and the risk of secondary contamination [27,28]. Generally viewed positively as a natural, non-intrusive approach, bioremediation can be customized for specific contaminants and site conditions by selecting appropriate microbial strains or plants for phytoremediation [4,30,31]. More than just removing pollutants, bioremediation contributes to soil fertility and structure improvement, fostering healthy ecosystem restoration. It is typically less energy-intensive compared to processes like incineration or advanced chemical treatments. A key benefit of bioremediation is its ability to fully break down organic pollutants, unlike some physical or chemical methods that might only transfer contaminants to another medium. This holistic approach not only cleans but also revitalizes contaminated environments. Biological remediation, while efficient and sustainable for environmental cleanups, faces challenges such as extended timeframes, especially in field applications, and unpredictable process durations under suboptimal conditions [3,25]. Its efficacy is selective; heavy metals, for instance, are not biodegradable but can only be transformed or immobilized, and heavier PAHs degrade slowly, requiring strategic consideration of soil contamination levels and microbial interactions [32]. Environmental factors like temperature, pH, and nutrient availability significantly impact bioremediation, with adverse conditions potentially halting the process. Incomplete contaminant removal could lead to the accumulation of potentially toxic intermediates, emphasizing the need for precise planning and adaptation in bioremediation strategies. Techniques such as bioventing and biosparging, while effective for low molecular weight PAHs, encounter difficulties in soils co-contaminated with heavy metals, as illustrated in Fig. 2 [3,33,34]. Methods like landfarming and composting show reduced efficacy for both PAHs and heavy metals [35–38]. Phytoremediation, incorporating phytodegradation and phytoextraction, is promising in extensive areas with low to moderate contamination [35–38]. A key challenge in bioremediation is the limited bioavailability of PAHs in soil, attributed to their hydrophobic nature and strong sorption to soil organic matter, hindering biodegradation [39]. PAH concentrations typically peak in surface soil and decrease with depth [40–43].

The use of exotic or genetically modified microbes in bioaugmentation carries ecological risks, such as disrupting local microbial communities or causing horizontal gene transfer. Genetically modified organisms (GMOs) in bioremediation, while broadly accepted, may face regulatory and public acceptance challenges. Certain bioremediation processes, especially those involving biosurfactants, could mobilize contaminants, thereby raising groundwater contamination risks if not well-managed [44]. Continuous monitoring and control are essential to ensure effectiveness and prevent secondary contamination. Bioremediation projects require tailored designs for specific sites and contaminant profiles, demanding thorough initial testing and ongoing monitoring. Biological remediation techniques, despite their viability for environmental cleanup, necessitate careful planning, monitoring, and management. To enhance these strategies, ongoing research is crucial, focusing on the selection and genetic modification of plant species and the isolation and enhancement of microbial strains. Integrating biological methods with other remediation techniques may yield more effective and efficient soil decontamination outcomes.

1.1.3. *Chemical remediation technologies*

Chemical remediation has been effective in breaking down contaminants such as petroleum hydrocarbons in contaminated soils. Suitable for both in situ and *ex situ* applications, it encompasses methods like surfactant flushing, chemical oxidation, and nanoparticle usage (Fig. 3) [4,44–49]. Especially apt for sites with complex pollutant mixtures, including dense PAHs and heavy metals, chemical remediation excels in harsh environmental conditions where biological or physical methods

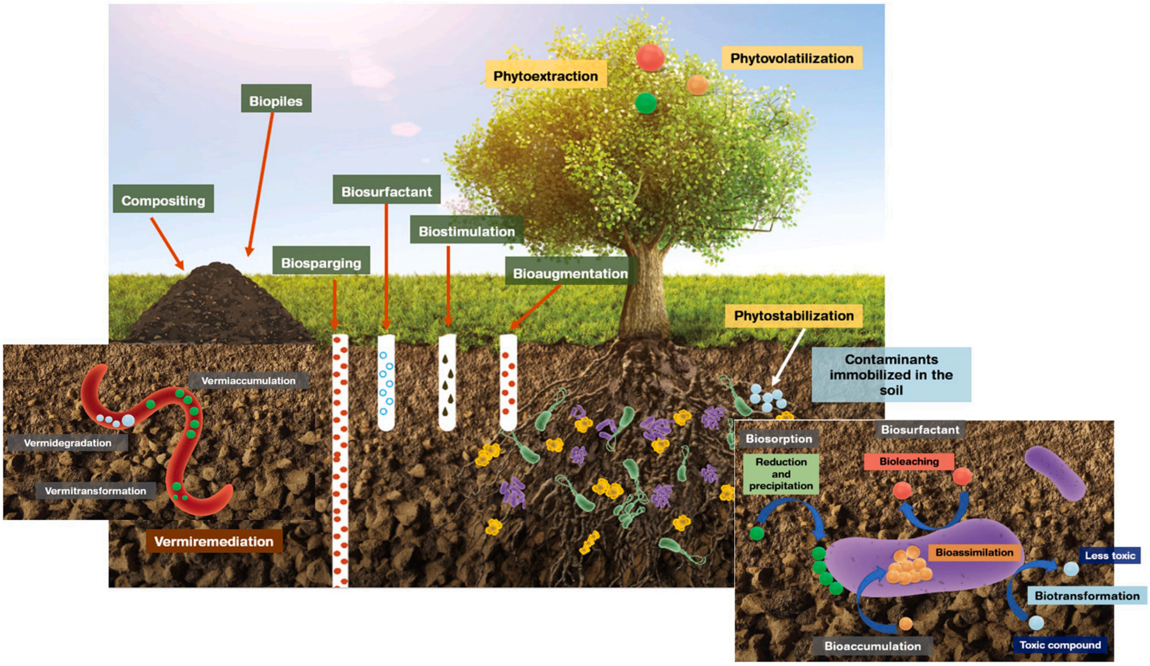

Fig. 2. Biological treatment. (1) Bioremediation. Biopile: Soil is excavated and mixed with amendments into compost piles. Compositing: Contaminated soils is mixed with organic waste. Biosparging: Introduce indigenous microorganisms in the saturated zone. Biosurfactant: Addition of surface-active compounds produced at the microbial into soil. Biostimulation: addition of nutrients to soil. Bioaugmentation: introducing microorganisms into soil. Phytoextraction: Accumulation of contaminants into plant organs. (2) Phytoremediation. Phytovolatilization: Uptake and transport of contaminants into the atmosphere. Phytostabilization: Reduce the mobility of contaminants in soil. (3) Vermiremediation: Use of earthworms to biodegrade chemicals by burrowing cycle, ingestion, bioaccumulation, and biotransformation.

may falter. Chemical remediation stands out for its rapid contaminant removal [50], an essential feature in situations demanding swift environmental hazard mitigation. It employs advanced oxidation processes capable of completely mineralizing organic pollutants into non-harmful substances like water and CO_2. This method's strength lies in the precision of controlling process parameters, ensuring predictable and consistent results. Such adaptability makes it suitable for diverse site conditions and various contaminant types. Chemical remediation excels in reducing high concentrations of PAHs and heavy metals, a task often more challenging for biological and physical approaches. The preference for in situ techniques over *ex situ* is due to the high costs related to soil excavation. In chemical oxidation, soil is mixed with oxidants like iron, hydrogen peroxide, or potassium permanganate ($KMnO_4$). While surfactants are used to solubilize contaminants for easier extraction, their effectiveness can vary based on soil composition, particularly in clay-rich soils [51–53]. The necessity for multiple applications of surfactants in chemical remediation can escalate overall costs. Selecting the right surfactant type, including anionic, non-ionic, and biosurfactants, is crucial due to their varying efficiencies in removing contaminants and influencing microbial activity [53–55]. Combining non-ionic and anionic surfactants has been suggested to enhance PAH soil remediation [56,57]. The effectiveness of surfactant-enhanced remediation in co-contaminated soils, especially for removing compounds like phenanthrene and heavy metals using surfactant-EDTA mixtures, is an area that requires further exploration [58–60].

Advanced Oxidation Processes (AOPs), a subset of chemical oxidation, effectively decompose organic contaminants like PAHs. These processes expedite oxidation in soil, characterized by high efficiency and adaptability. AOPs operate primarily through free radical generation, utilizing agents such as hydrogen peroxide, Fenton's reagents, permanganate, ozone (O_3), and persulfate [48,61–63]. Fenton oxidation, particularly effective against highly toxic and biodegradable pollutants, depends on factors like temperature, pH, and the concentrations of oxidants and catalysts [62–64]. The effectiveness of Fenton processes is influenced by soil properties, necessitating precise control over aspects like hydrogen peroxide dosage and reaction conditions. Challenges at pilot scales include dosing uncertainties and variable outcomes [63–65]. Stoichiometric oxidant demand (SOD) is crucial in Fenton processes but is complicated by diverse soil conditions [61]. Incremental H_2O_2 addition in Fenton-based AOPs, potentially with chelating agents, has been shown to more effectively remove TPHs than rapid addition methods [66].

Chemical remediation techniques, despite their effectiveness, have several drawbacks. They may lead to secondary pollution by producing harmful by-products or transforming contaminants into other toxic substances, often requiring additional treatment [67]. The associated costs of chemicals, specialized equipment, and energy, particularly for advanced methods, render these techniques relatively expensive [1]. Implementing chemical remediation requires specialized knowledge and expertise due to its technical complexity. In environments with complex contaminant mixtures, chemical treatments may not achieve complete remediation, leaving some pollutants unaddressed. *In situ* applications can disturb the site, potentially affecting soil properties and groundwater quality. Additionally, these methods can encounter regulatory and public resistance, particularly in residential or ecologically sensitive areas [3,68,69]. Soil characteristics like pH, organic matter content, and moisture levels significantly influence the effectiveness of chemical treatments. Some methods might not ensure the long-term stability of the contaminants, necessitating continuous monitoring and possible future interventions. Moreover, certain chemical processes, especially those that generate reactive species or involve heating, are energy-intensive [3,70].

In summary, chemical remediation, including AOPs, is highly effective in complex contaminant situations, such as those with heavy PAHs and metals, and in harsh environments. However, their adoption requires careful assessment of environmental impacts, costs, technical complexities, and long-term effectiveness. The development of integrated remediation strategies, combining physical, chemical, and biological methods, is crucial for efficient, cost-effective, and eco-friendly management of PAH contamination in soils. (Table 1).

1.2. *Dissecting soil remediation: PAH and heavy metal treatments*

In treating soils contaminated with PAHs and heavy metals, it's

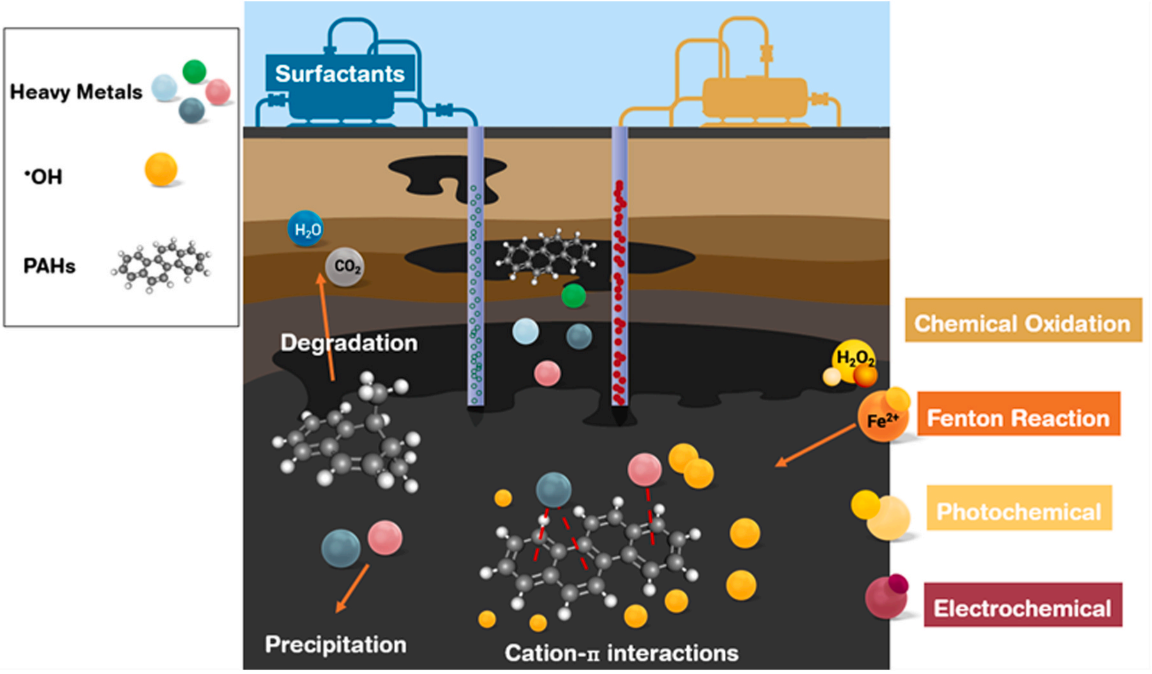

Fig. 3. Illustrate the Cation-π interactions that take place between PAHs and heavy metals. There are two chemical treatments, surfactant, and chemical oxidation. The chemical oxidation is divided into Fenton reaction, photochemical and electrochemical reactions. It shows the ability of these reactions in breaking the bond between PAHs and heavy metals, leading to the degradation of PAHs and precipitation of heavy metal in co-contaminated soil.

Table 1
Comparative Advantages and Disadvantages of Biological, Physical, and Chemical Remediation Techniques.

Advantages	Disadvantages
Physical Remediation Techniques	
Quicker remediation compared to biological or chemical methods.	Costly due to specialized equipment, energy consumption, and soil transport.
Effective for a wide variety of contaminants, including non-biodegradable ones.	Risk of secondary contamination if not managed properly.
Greater control over the remediation process with precise parameter adjustment.	Generation of waste that needs safe disposal.
Reduced liability as contaminants is physically removed.	Disruptive to the site and potential harm to ecosystems and infrastructure.
Can be applied in situ or *ex situ*, offering flexibility.	May not effectively treat deeply buried or diffused contaminants.
Potential recovery of valuable materials from contaminated soils.	Energy-intensive methods contribute to higher operational costs and carbon footprint.
Integration with chemical or biological methods in multi-step strategies.	Contaminants often concentrated, requiring further treatment or disposal.
	Public opposition (NIMBY syndrome) due to noise, dust, and disruption.
	Not always scalable or economically feasible for large-scale contamination.
	Soil properties may change post-remediation, limiting future use.
Biological Remediation Techniques	
Environmentally compatible, often leading to complete mineralization of contaminants.	Longer remediation times compared to chemical or physical methods.
Generally, less expensive with fewer equipment and resource requirements.	Not all contaminants are biodegradable (e.g., heavy metals).
In situ remediation reduces carbon footprint and secondary contamination risks.	Highly dependent on environmental factors (temperature, pH, etc.).
Publicly acceptable as a natural, non-invasive process.	Potential accumulation of toxic intermediate compounds in some cases.
Tailorable to specific contaminants and site conditions.	Requires thorough initial testing and ongoing monitoring.
Can enhance soil fertility and structure, promoting healthy ecosystems.	Ecological risks with non-native or genetically modified organisms.
Generally lower energy requirements compared to high-energy processes.	Continuous monitoring and control are essential.
Complete breakdown of organic pollutants into harmless end-products.	Regulatory hurdles and public skepticism with GMOs.
	Potential mobilization of contaminants if not managed properly.
Chemical Remediation Techniques	
Well-suited for complex mixtures of pollutants, including heavy concentrations of PAHs and heavy metals.	Potential production of harmful by-products or transformation into toxic substances, necessitating further treatment.
Effective in challenging and harsh environmental conditions where other methods might be less effective.	Costs associated with chemicals, specialized equipment, and energy can be relatively high.
Rapid contaminant removal is crucial in scenarios requiring quick mitigation of environmental hazards.	Technical complexity often demands specialized knowledge and expertise for implementation.
Advanced oxidation processes can achieve complete mineralization of organic pollutants.	In some complex contaminant environments, chemical treatments may not fully remove all pollutants, leading to incomplete remediation.
Precision in controlling process parameters allows for predictable and consistent outcomes.	*In situ* chemical treatments can disrupt the site and potentially alter soil properties or impact groundwater quality.
Adaptable to a wide range of site conditions and contaminant profiles.	Potential regulatory hurdles and public skepticism, especially in sensitive areas.
Effective at targeting and reducing high concentrations of both PAHs and heavy metals.	Effectiveness influenced by soil characteristics like pH, organic matter content, and moisture levels.
	Some methods may not guarantee long-term stability of contaminants, requiring ongoing monitoring and potential future intervention.
	Certain chemical processes, especially those involving reactive species or heating, can be energy intensive.

essential to differentiate between their reaction mechanisms and schemes. Developing a reaction mechanism entails a deep dive into the specific reactions of PAHs and heavy metals, a task marked by its complexity due to various biochemical, chemical, and physical interactions. For PAHs, this might involve microbial degradation pathways, where enzymes break down PAH molecules into less harmful components. Heavy metal remediation, on the other hand, could involve adsorption, precipitation, or complexation processes. Characterization techniques such as Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning electron microscopy (SEM), and Brunauer-Emmett-Teller (BET) surface area analysis provide valuable insights. FTIR helps identify functional groups and organic compounds related to PAHs [71–74]. XRD offers insights into the crystalline structure of soils, crucial for understanding heavy metal immobilization. SEM shows the morphology of soil particles, including heavy metal aggregation, while BET analysis assesses soil particle surface area, essential for adsorption processes. Given the complexity, delving into detailed reaction mechanisms is beyond this review's scope and warrants more in-depth research. Regarding reaction schemes, they visually represent the initial contamination state, applied remediation strategies, and the final condition of the soil. These schemes could depict the microbial degradation of PAHs into water and CO_2 in bioremediation processes or the stabilization of heavy metals in the soil matrix through solidification/stabilization methods. Accurate determination of reaction mechanisms and schemes requires comprehensive data from these characterization methods, adapted to specific soil and contaminant characteristics. This necessitates a multidisciplinary approach involving soil chemistry, microbiology, and environmental engineering expertise. This review, therefore, focuses on briefly discussing the reaction schemes associated with the three main remediation approaches: physical, biological (bioremediation), and chemical remediation.

Physical remediation methods offer a diverse set of solutions tailored to meet the unique needs of contaminated sites. The choice of technique hinges on various factors, including contaminant type and concentration, soil properties, intended post-treatment soil use, cost, and regulatory compliance. Each technique in physical remediation systematically focuses on separating, recovering, and containing contaminants to minimize environmental impact (Fig. S1-A). These techniques primarily aim to separate and contain contaminants, distinguishing them from methods that chemically or biologically transform pollutants. They are especially effective for soils contaminated with a mix of organic pollutants, such as PAHs, and inorganic pollutants like heavy metals [75]. For instance, soil washing, and solidification/stabilization are key physical remediation strategies (Fig. S1-A) [76]. Soil Washing employs a washing solution, often augmented with additives, to detach contaminants from soil particles. For PAHs, surfactants are used to enhance solubility and separation, while chelating agents form soluble complexes with heavy metals. The process involves mechanical techniques like sieving, sedimentation, flotation, and filtration to separate contaminants from the soil (Fig. S1-A) [77]. Additional methods like high-pressure jets, scrubbing, or ultrasonic waves can further loosen the bond between soil and pollutants. Post-washing, contaminants are removed from the solution using techniques like air stripping or adsorption for PAHs, and chemical precipitation or ion exchange for heavy metals (Fig. S1-A) [27]. Solidification/Stabilization binds contaminants within a solid matrix using materials like cement, lime, or clay, thereby reducing their mobility. Chemical reactions between binders and contaminants stabilize heavy metals, forming less soluble compounds within the soil. Post-treatment, the soil is often enclosed or capped to prevent exposure and reduce leaching risks [1,27].

Biological remediation strategies, particularly bioremediation methods, harness biological processes, mainly microbial metabolism, to address contaminants in soils affected by PAHs and heavy metals, as depicted in Fig. S1-B. This method utilizes the inherent capabilities of microorganisms, positioning it as a crucial strategy for lessening the environmental burden of such pollutants [1]. The cornerstone of bioremediation for PAHs lies in microbial degradation. Specific bacteria and fungi strains utilize PAHs as a carbon and energy source, employing enzymes to convert these compounds into less harmful substances [78]. Enzymatic breakdown is central to this process, with enzymes like dioxygenases and monooxygenases introducing oxygen into PAH molecules. This initiates a chain of reactions, culminating in the formation of diols, quinones, and eventually smaller, less toxic molecules.

Enhancing bioremediation involves strategies like bioaugmentation and biostimulation. Bioaugmentation introduces PAH-degrading microorganisms into the soil, bolstering biodegradation, while biostimulation involves supplying nutrients and oxygen to invigorate the native microbial population, thereby accelerating biodegradation [79, 80]. This often involves tailoring environmental conditions, such as soil pH, temperature, and nutrient content, to optimize microbial activity (Fig. S1-B) [1,4]. For heavy metals, bioremediation focuses on transformation or immobilization, given that metals are not degradable. Microbial biosorption and bioaccumulation are pivotal here, with microorganisms binding heavy metals onto their cell walls or internalizing them. Phytoremediation also contributes, with specific plants accumulating heavy metals in their tissues, sequestering, or transforming them into less harmful forms (Fig. S1-B). The reaction scheme for heavy metal bioremediation encompasses steps like bioprecipitation, where microbial activity alters metals' oxidation states, precipitating them as insoluble compounds. Bioleaching, more prevalent in mining, sees acidophilic microbes solubilize metals by producing acids. These processes effectively reduce heavy metals' mobility and toxicity in soils (Fig. S1-B). Bioremediation's success hinges on environmental factors, necessitating the monitoring and optimization of conditions for effective treatment. This includes meticulous soil and contaminant characterization, selecting suitable microbial cultures, and adhering to regulatory standards. The complexity of bioremediation emphasizes the importance of understanding microbial ecology and soil science, alongside rigorous planning and monitoring. Techniques like gas chromatography-mass spectrometry (GC-MS) for organic compounds and inductively coupled plasma mass spectrometry (ICP-MS) for metals are instrumental in tracking bioremediation progress and effectiveness [81–83]. This holistic approach aims to restore the soil to a condition fit for its intended post-remediation use.

Chemical remediation for soils afflicted with PAHs and heavy metals involves an array of chemical processes aimed at transforming or removing these contaminants safely and effectively (Fig. S1-C). The success of these methods relies on the contaminants' nature and the chosen treatment techniques. For PAHs, oxidizing agents like H_2O_2, O_3, and $KMnO_4$ are pivotal, dismantling the complex aromatic structures through oxygen addition, forming intermediates primed for further degradation and eventual mineralization into CO_2 and water [1,84–86]. Catalysts such as iron (in Fenton's reaction) or ultraviolet light (in photochemical oxidation) enhance these oxidation reactions (Fig. S1-C).

In addressing heavy metals, strategies like chemical reduction and immobilization are crucial. Agents like zero-valent iron (ZVI), and sulfides reduce metals' oxidation states, diminishing their solubility and bioavailability [87]. This often leads to stable, insoluble metal compounds, reducing environmental leaching risks. Soil pH adjustment is also fundamental, as metal compound solubility is pH-dependent, with alkaline materials like lime used for pH modulation (Fig. S1-C). AOPs employ robust oxidants and catalysts to produce reactive radicals, such as hydroxyl radicals (•OH), which non-selectively degrade organic contaminants like PAHs and stabilize metal species [88]. The goal is comprehensive mineralization of organic contaminants and stabilization or adsorption of metals onto soil constituents (Fig. S1-C). The execution of chemical remediation requires meticulous control and monitoring to ensure effective treatment and prevent harmful by-product formation. Method selection depends on an in-depth understanding of soil characteristics, contaminant types and levels, environmental factors, and cost considerations. Compliance with regulatory standards and potential impacts on soil fertility and ecology are also pivotal in planning and execution (Fig. S1-C). In essence, chemical remediation presents a suite of potent decontamination methods. However, its successful application demands a profound grasp of chemistry, engineering, and environmental science, alongside meticulous planning, monitoring, and adherence to safety and environmental protocols. This approach ensures a balance between effectiveness and economic viability, especially for extensive or long-term projects. Our research highlights the necessity for a comprehensive and nuanced approach to soil cleanup, one that acknowledges the complex interplay of different pollutants. As the prevalence of co-contaminated sites increases, the call for innovative and thorough remediation solutions intensifies. This study lays critical groundwork for future development of targeted, sustainable strategies to address co-contaminated soils effectively.

1.3. Overview of emerging techniques in soil remediation: genetic engineering and nanotechnology

Genetic plant engineering aims to enhance specific traits in plants or microorganisms, improving their adaptability to harsh environments and effectiveness in removing contaminants. This includes inducing gene expression to boost phytoextraction in plants and augmenting degradation capabilities in plant-associated bacteria, such as endophytic and rhizospheric bacteria, for petroleum hydrocarbon remediation [89–92]. Recent advancements have led to the creation of superorganisms with heightened abilities to address pollutants in co-contaminated sites, including heavy metals and PAHs. Engineered microbial strains have shown increased effectiveness in bioremediation and in raising contaminant bioavailability [93–98]. For example, Sarma *et al.* (2019) showed that genetically modified plants and microbial consortia, supported by biochar, enhanced PAH and heavy metal removal from contaminated soil. Pseudomonas putida, engineered for rhamnolipid synthesis regulation, exhibited accelerated pyrene degradation in PAH-contaminated soils [99]. However, applying genetic engineering to co-contaminated soil remediation faces challenges like unpredictable gene interactions, risks to microbial diversity, and the discrepancy between lab and field results, necessitating more research for safe and effective use [100,101].

In soil remediation, nanotechnology, particularly through nanoparticles, is gaining prominence. Iron-based nanoparticles, such as nanoscale ZVI and magnetite nanoparticles, have been effective in stabilizing contaminants like heavy metals and PAHs. Studies have successfully used iron magnetic nanoparticles to immobilize As and PAHs in soil, reducing phytotoxicity [102,103]. Green synthesis of nanoparticles using microorganisms and plant extracts presents a sustainable, cost-effective approach for contaminant stabilization. Examples include bentonite-green tea extract-nanoscale ZVI for Cr stabilization and green synthesized iron oxide nanomaterials for As transformation [103,104]. Despite its promise, nanotechnology in soil remediation, especially for co-contaminated soils, requires further research to fully understand its potential and implications.

Genetic engineering and nanotechnology present promising advancements in soil remediation but carry associated risks. Genetic engineering could potentially disrupt genetic stability and impact ecosystems, while nanotechnology demands attention to environmental safety. Effective application of these techniques requires deep insights into soil ecosystems' complexities. Prioritizing ecological safety and real-world applicability is essential to transition these methods from lab research to successful field implementations.

1.4. Overview of combined remediation strategies

When tackling PAHs and heavy metals in co-contaminated soils, single-method remediation often encounters limitations due to complex external interactions. Combining various remediation technologies, such as biological-biological, chemical-biological, and physical-chemical approaches, is increasingly acknowledged for effectively removing complex contaminants. Integrating biostimulation with phytoremediation or bioaugmentation has been shown to outperform individual methods. This synergy, particularly with plants like ryegrass, not only degrades PAHs but also stimulates microbial growth for more efficient contaminant removal [105–110]. The use of bio-carriers like plant residues and biochar has enhanced microbial activity in PAH-impacted soils [111–114]. Chemical oxidation, especially Fenton-AOP combined with bioremediation, has been more effective in PAH removal than standalone methods [115–119]. Electrokinetic treatments paired with phytoremediation demonstrate significant success in removing both PAHs and heavy metals [11,12,120], and their integration with oxidants and surfactants further improves TPH removal. Recent advances include electrokinetic-Fenton treatments using cost-effective materials for efficient PAH degradation [84,121]. Nanotechnology, when combined with phytoremediation, such as nano-hydroxyapatite with ryegrass, effectively removes heavy metals like Pb [104–106]. Additionally, genetically engineered microorganisms used alongside phytoremediation have enhanced the joint degradation of contaminants. A comprehensive strategy involves a three-step approach combining soil washing, electrochemical AOP, and bioremediation, targeting contaminants from multiple perspectives to save resources and reduce costs [27,34,70,122–127].

Combined remediation technologies, merging physical, chemical, and biological methods, offer efficient, cost-effective, and eco-friendly solutions for soil decontamination. These combined approaches surmount the limitations of single-method treatments and improve overall efficacy in removing PAHs and heavy metals from co-contaminated soils. The effectiveness of these integrated strategies hinges on an in-depth understanding of the contaminated site and careful coordination among various remediation techniques.

1.5. Overview and analysis of remedial costs in environmental technologies

As environmental remediation technologies evolve to meet contemporary demands, their enhancements extend beyond efficacy and speed to encompass economic, environmental, and social impacts, as well as adaptability to changing climates. A key challenge lies in accurately estimating remediation costs, influenced by location-specific conditions and varying treatment durations. Remediation technologies are categorized into short, medium, and long-term treatments, each with distinct cost implications. The variability of conditions across different countries adds complexity to cost estimation, with published studies providing estimates that may not always align with practical applications in diverse contexts [128–134]. Physical remediation, while resource-intensive, involves substantial personnel, materials, and by-product management costs. In large-scale projects, these costs escalate due to the extensive labor and equipment needed [4]. Chemical remediation offers efficiency, but post-treatment chemical removal incurs additional expenses, such as the significant costs associated with chemical oxidants for larger sites. Biological remediation, generally more cost-effective, can lead to increased costs over time due to longer treatment durations [132]. Combining different remediation methods can provide more cost-effective solutions, balancing the resources and time needed compared to single-method approaches. However, these costs vary greatly with the project's scale and complexity. Integrated remediation approaches aim to shorten treatment times and reduce overall costs relative to traditional methods. Determining the most cost-effective approach requires a comprehensive analysis of factors including remediation investigation, bench-and pilot-scale testing, regulatory compliance, construction, startup, as well as ongoing operation and maintenance expenses [135].

Despite cost being a crucial aspect of remediation planning, significant variations across different regions necessitate extensive research and comparative analysis to identify the most economically viable remediation method, especially for large-scale decontamination projects. Without a clear understanding of these varying costs, effective decision-making in environmental remediation remains a challenge.

1.5.1. Central themes of this literature review

Over the years, chronic oil spills have caused significant changes in the physical and chemical properties of the soil system, posing harmful effects on human health [27,136]. Petroleum hydrocarbons, a serious geo-environmental issue, travel through various environments such as air, water, and soil until they settle and accumulate in the soil [27,136]. Once toxic materials infiltrate the soil medium, they continuously undergo absorption, decomposition, migration, and transformation within the physical, chemical, and biological compartments of the soil [27, 137]. Crude oil often contains metals like iron, copper, lead, and cadmium, further complicating the soil environment and making the implementation of effective remediation technologies challenging [138, 139]. The term "co-contamination" arises from the co-existence of multiple types of pollutants in a particular environment, complicating both remediation efforts and risk assessments compared to sites with only a single form of contamination. The concept of "co-contamination" is rooted in the simultaneous presence of diverse pollutants in a specific setting, making the remediation process and risk evaluation more intricate than in locations with just one type of contaminant. There is a notable lack of understanding regarding the co-occurrence of PAHs and heavy metals in contaminated soils, representing a significant gap in existing research [70]. Moreover, only a few studies have attempted to develop approaches that can effectively tackle both contaminants in field studies [140,141]. Conducting a comprehensive review is essential for successful research; however, the exponential growth in online technologies and the sheer number of published articles make it increasingly challenging and time-consuming to collect relevant data from such massive datasets.

To address these challenges and improve the efficiency of literature review and research, artificial intelligence-assisted (AI) tools have emerged as the next-generation research platform [142]. These AI tools empower researchers from different disciplines to explore academic literature easily and rapidly, thereby enhancing our understanding of the published knowledge relevant to specific issues, research areas, or theories. The primary objective of this review is to utilize AI and big data analytics to examine the complexities within the soil system that hinder the efficiency of remediation technologies for removing PAHs and heavy metals in co-contaminated sites. The review aims to shed light on emerging and integrated remediation approaches that offer better alternatives for treating co-contaminated soils. By identifying and analyzing gaps in the current knowledge of developing remediation methodologies, this paper aims to establish a knowledge base for future studies in this area.

To achieve these objectives, the review employs AI-assisted tools for literature review and bibliography analysis. A combined search system using traditional academic search methods and various AI tools is used to provide valuable quantitative and visual information about research trends, knowledge gaps, and research networks. This approach ensures comprehensive coverage and up-to-date information related to the topic of interest.

The review focuses on four main objectives:

1. Exploring the Mechanisms of Interaction Between Heavy Metals and Polycyclic Aromatic Hydrocarbons (PAHs) in Contaminated Soils: Implications for Remediation Effectiveness.
2. Comparative Analysis of Limitations and Challenges in Combined versus Single Treatment Techniques for Remediation of Co-Contaminated Soils: Assessing Efficiency, Consistency, and Specificity Across Contaminant Types.
3. Assessing the Effectiveness of Integrated Biological, Chemical, and Physical Remediation Approaches in Co-Contaminated Soils: Evaluating the Impact of Diverse Agents on Heavy Metals and PAHs under Varying Environmental Conditions.
4. To determine whether AI-powered search tools provide a superior alternative to traditional search methodologies in conducting comprehensive systematic reviews.

By addressing these objectives, the review aims to contribute to filling the research gap in understanding and effectively addressing soil contamination by both PAHs and heavy metals. This knowledge will facilitate the development of more efficient and sustainable remediation strategies for co-contaminated sites, ensuring the protection of both the environment and human health.

The novelty of this work lies in its holistic and innovative approach to addressing soil contamination by crude oil, specifically targeting sites co-contaminated with heavy metals and PAHs. This comprehensive review fills a crucial research gap by elucidating the complex interactions between heavy metals and PAHs and examining the efficacy of various remediation strategies in diverse environmental conditions. A key feature of this study is the integration of AI and big data analytics, employing tools like Litmaps.co [143], ResearchRabbit [144], and MAXQDA (VERBI Software, 2022) [145] for an in-depth and precise literature analysis, a method distinguishing it from conventional reviews.

The review delves into multidimensional research questions, ranging from interaction mechanisms of contaminants to the comparative effectiveness of combined and single-treatment remediation methods. It also explores the application of AI-powered tools in conducting systematic reviews, an innovative aspect in itself. The study's unique insights into cation-π interactions, the role of soil properties, and the impact of factors like nickel presence on pollutant behavior mark a significant advancement in understanding soil contamination. Furthermore, the trend analysis of remediation strategies, highlighting a shift towards combined biological methods, and the detailed examination of agents like *Medicago sativa L.*, *Solanum nigrum L.*, biochar, and EDTA in phytoremediation offer a comprehensive understanding of effective soil treatment. The inclusion of Life Cycle Assessment (LCA) results adds a vital perspective on the environmental and economic impacts, advocating for a balanced and site-specific approach to remediation. Overall, this review significantly contributes to the field by amalgamating various remediation methods and cutting-edge research tools to propose effective, sustainable solutions for soil decontamination in the face of oil, heavy metals, and PAHs contamination.

2. Methods

The emerging field of AI techniques is projected to expand substantially in the coming years. Literature reviews are increasingly crucial in various scientific domains, yet the manual sifting through vast amounts of research articles is both time-consuming and prone to errors. A methodical approach can mitigate potential biases and inaccuracies in literature search and analysis. Currently, scholars manually screen a large volume of studies, a process that is inefficient and error-prone due to the limited relevance of most screened articles. To optimize the process of conducting systematic reviews, we evaluated multiple AI-assisted tools for literature analysis, focusing on criteria such as accuracy, completeness, consistency, and usefulness among others. Based on our evaluation of 10 AI tools, we identified Litmaps and ResearchRabbit as the most effective platforms for our research needs. These tools excel in text mining and offer robust features for visualizing a large dataset of articles, thus facilitating a comprehensive literature analysis. Initiating new research typically necessitates a thorough examination of existing scientific literature to understand the context and identify pertinent studies.

Our goal is to offer insightful quantitative and visual data on research patterns, knowledge voids, and scholarly networks in the realm of soil remediation for co-contaminated sites. Utilizing Litmaps and ResearchRabbit, we aimed to refine and expedite the literature review process [146,147]. These AI-powered tools sourced data from multiple providers like Crossref and Semantic Scholar, enabling us to pinpoint a wide array of pertinent articles for our review. This expansive data analysis ensured a comprehensive and in-depth review, helping to bridge existing research gaps and stay updated on recent publications. The incorporation of AI tools into our literature review methodology enabled us to gain valuable insights and establish meaningful links between diverse studies in co-contaminated soil remediation. Using Litmaps and ResearchRabbit amplified the rigor and depth of our literature search, providing a solid foundation for our systematic review.

The systematic review conducted a comprehensive analysis to address three research questions related to soil remediation for PAHs and heavy metal co-contaminated sites. The formulated research questions are as follows:

1. What are the interaction mechanisms between heavy metals and PAHs in contaminated soils, and how do these affect the efficacy of different remediation methods?
2. What are the challenges and limitations of combined remediation techniques for co-contaminated soils compared to single-treatment methods in terms of efficiency, stability, and specificity?
3. How do various factors influence the effectiveness of biological, chemical, and physical remediation methods, both individually and combined, in co-contaminated soils, and what role do specific agents play in the degradation, immobilization, or removal of heavy metals and PAHs under diverse environmental conditions?
4. Do AI-powered search tools offer a superior alternative to conventional search methodologies for executing an exhaustive systematic review?

To initiate the review process, we employed traditional search systems, including popular databases like ERIC (EBSCO), JSTOR, MEDLINE (Ovid), PubMed, ScienceDirect, and Google Scholar. These databases served as the foundation for our search, and we used a set of relevant keywords related to oil, petroleum, soil, contamination, total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAHs), heavy metals, remediation, biological, physical, chemical, emerging technologies, and combined remediation. These keywords were mixed and matched in each search to ensure a comprehensive retrieval of relevant articles.

After gathering articles from the traditional search systems, we identified them as seed articles for further analysis using AI-assisted tools, specifically the Litmaps platform. The Litmaps platform was utilized to search for articles related to the seed articles in data providers like Crossref and Semantic Scholar, resulting in over 10,000 findings dating back to 2000. To streamline the process, we created two maps categorized into PAHs and heavy metals. Further in-depth searches were conducted using keywords such as "soil," "methodology," "technology," "remediation," "chemical," "physical," "biological," and "combined," which led to the identification of 116 articles. Subsequently, a final map was created by combining the PAHs and heavy metals categories, and articles that overlapped between the two were labeled as co-contaminated soil.

To reinforce the search, we utilized the ResearchRabbit platform with the same seed articles. This search yielded 2081 articles, which were categorized as similar work, earlier work, and later work. We applied filters to the abstract section of the articles, including publication year (2000–2022), and keywords related to co-contamination, co-existence, co-occurrence, soil, PAH, heavy metals, remediation, chemical, physical, biological, single treatment, and combined treatment. After filtering, we selected 72 articles that met our search criteria using both platforms.

The relevant articles were imported into MAXQDA software for further analysis. Based on our first specific research question on methodologies for removing PAHs and heavy metals, we developed certain keywords that could also address the second and third research questions. In MAXQDA, we utilized a single coding approach with categories such as "type," "method," "experiment," "analysis," "results," "conclusion," "source," "PAH," and "heavy metal." Sub-codes were created within each category to further analyze the data, including chemicals, microorganisms, physical parameters, concentration, field and laboratory studies, extraction, analysis, increase, decrease, percentage, and concentration. Additional sub-codes "different" and "same" were added under the method and result codes to address the "how," "why," and "what" aspects related to the parameters used in remediation technologies, differences between laboratory and field studies, and the effectiveness of combined treatment techniques compared to single

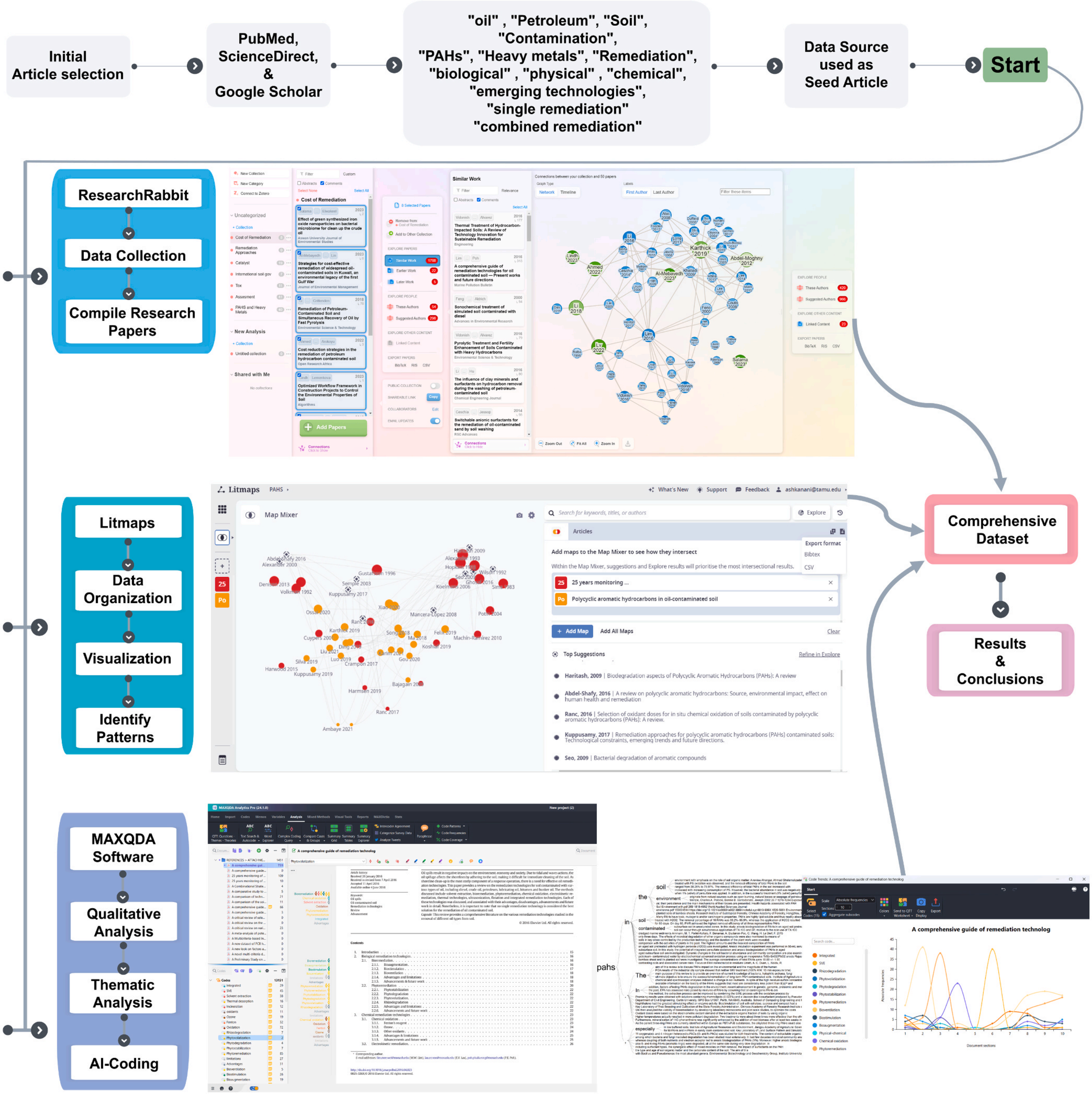

Fig. 4. Methodological Approach: We used a mix of traditional databases like ERIC, JSTOR, and PubMed, and AI tools like Litmaps and ResearchRabbit to select articles for review. MAXQDA software was used for final assessment and coding of the selected articles.

treatment techniques. The iterative reading and coding process allowed for comprehensive analysis and removal of overlaps. Finally, MAXQDA's inductive coding process, including modularity algorithms and resolution variables, was employed to extract relevant text information and establish connections between the results. This mixed-search method enabled a holistic approach to comprehensively answer the research questions and provide valuable insights into soil remediation for co-contaminated sites.

In MAXQDA, we employed a two-step coding approach to analyze the qualitative data from the selected articles. The first step involved using a single coding approach, where we identified and established the main categories for analysis. These categories were "type," "method," "experiment," "analysis," "results," "conclusion," "source," "PAH," and "heavy metal." These categories served as the foundation or building blocks of our analysis. In the second step, we utilized a coding-tree approach to further delve into the data and extract more specific insights. Within each of the main categories, we created sub-codes to capture specific information related to the research questions. The sub-codes included "chemicals," "microorganisms," "physical," "concentration," "field," "laboratory," "extraction," "analysis," "increase," "decrease," "percentage," and "concentration." Furthermore, under the "method" and "result" codes, we introduced additional sub-codes "different" and "same." These sub-codes were instrumental in addressing the "how," "why," and "what" aspects related to the parameters used in each remediation technology and the variations between laboratory and field studies. Additionally, they helped us evaluate whether combined treatment techniques could effectively overcome the issues associated with single treatment techniques. To ensure comprehensive and accurate analysis, the reading and coding process was conducted multiple times. This iterative approach allowed us to code all relevant information from the articles while eliminating any overlaps or inconsistencies in our analysis. In the final phase, we utilized the inductive coding process in MAXQDA. This approach involved using modularity algorithms and resolution variables to extract relevant text information and establish connections between the results. The modularity algorithm, in combination with other variables, allowed for a more holistic approach to comprehensively answer our research questions. This mixed-search method, utilizing both traditional academic search systems and AI-assisted tools, enabled us to obtain valuable insights and address the complexity of soil remediation for co-contaminated sites in a thorough and effective manner (Fig. 4). The systematic review using MAXQDA as a qualitative data analysis tool served as a robust and reliable method to extract valuable information from the selected articles, facilitating a comprehensive and evidence-based conclusion to our research questions (Table 2).

Table 2 provides a comparison of various AI-based tools that were evaluated during the process of selecting the most appropriate tool for conducting the literature review. The table outlines key features and functionalities of each tool, enabling a better understanding of their capabilities and limitations. Litmaps utilizes data sources such as OpenAlex, Crossref, and Semantic Scholar, providing a wide range of articles for analysis. It offers excellent visualization capabilities, which enable researchers to explore research trends and relationships visually. However, to access extensive search options, membership is required. Litmaps has been considered an efficient tool for conducting literature reviews due to its extensive database and advanced visualization features. ResearchRabbit tool uses ORCID profiles and offers additional options like previous and future citations, making it an excellent choice for efficient literature review. Its ability to search and analyze citations based on profiles makes it highly effective for retrieving relevant articles. Maxqda is an AI-based qualitative data analysis tool, offering various features such as coding, analysis, reading, editing, paraphrasing, and importing of text documents and web pages. It allows for efficient exploration and summarization of content, generating frequency tables and charts, and statistical analysis of qualitative data. However, membership is required for full access to its advanced capabilities. CiteSpace utilizes data sources like WoS, Scopus, and others. Although it offers visualization capabilities, it lacks visualization features. It may not be the ideal choice for this study due to its limited ability to efficiently conduct literature reviews compared to other tools. VOSviewer, using data from WoS, Scopus, Wikidata, and other sources, offers excellent visualization capabilities. Its ability to create maps based on co-citations and co-authorships is valuable for identifying research networks. However, its primary focus is on visualization, and it may not be suitable for extensive literature review needs. Open Knowledge Maps tool has limited capabilities in which it relies on PubMed data and uses a text matching approach. Unfortunately, it lacks citation matching, making it less efficient for comprehensive literature review compared to other tools. Citation Gecko focuses on open DOI-to-DOI citations and offers excellent citation matching capabilities, making it a valuable tool for efficiently tracking citations. Inciteful utilizes data from Semantic Scholar, OpenAlex, Crossref, and OpenCitations. While it offers good efficiency, its limitation to analyzing two papers at a time may hinder comprehensive literature review. Connected Papers tool utilizes data from Semantic Scholars and provides good efficiency for certain literature review needs. However, it has limited functionality, restricting its broader application. Finally, the Citation tree uses data from Crossref and Semantic Scholar but is limited to analyzing only one paper at a time, which may not be ideal for conducting extensive literature reviews. Based on this comparison, Litmaps, ResearchRabbit, and MAXQDA were selected for the study due to their excellent efficiency, visualization capabilities, and compatibility with the research objectives. These AI-assisted tools significantly contributed to the comprehensive analysis of relevant articles, data extraction, and generation of valuable insights to address the formulated research questions effectively.

The PRISMA flow diagram in Fig. 5 illustrates the process of article selection. We began with three seed articles obtained from the traditional database searches and used Litmaps and ResearchRabbit to find highly related articles, resulting in 1000 and 2081 articles, respectively.

Table 2
Comparative Analysis of AI-based Tools for Literature Review Selection.

AI-Search Tools	Data Source	Visualization	literature review Efficiency	Website
1. **Litmaps**	OpenAlex, Crossref, Semantic Scholar	Yes	Excellent – membership for extensive search	https://www.litmaps.com
2. **ResearchRabbit**	ORCID profile	Yes	Excellent	https://www.researchrabbit.ai
3. **Maxqda**	AI-Qualitative Data Analysis	Yes	Excellent – requires membership	https://www.maxqda.com
4. **CiteSpace**	WoS and Scopus, and others	Yes	No	https://citespace.podia.com/
5. **VOSviewer**	WoS, Scopus, Wikidata, and others	Yes	Excellent tool	https://www.vosviewer.com/
6. **Open Knowledge Maps**	PubMed	Yes	No - Text matching tool, lacks citation matching	https://connect.ebsco.com/s/article/Concept-Map-Quick-Start-Guide?language=en_US
7. **Citation Gecko**	Open DOI-to-DOI citations	Yes	Excellent tool	https://www.citationgecko.com
8. **Inciteful**	Semantic Scholar, OpenAlex, Crossref, OpenCitations	Yes	Good - limited to two papers	https://inciteful.xyz
9. **Connected Papers**	Semantic scholars	Yes	Good – limited use	https://www.connectedpapers.com
10. **Citation tree**	Crossref and Semantic Scholar	Yes	Good – limited to one paper	https://www.citationtree.org

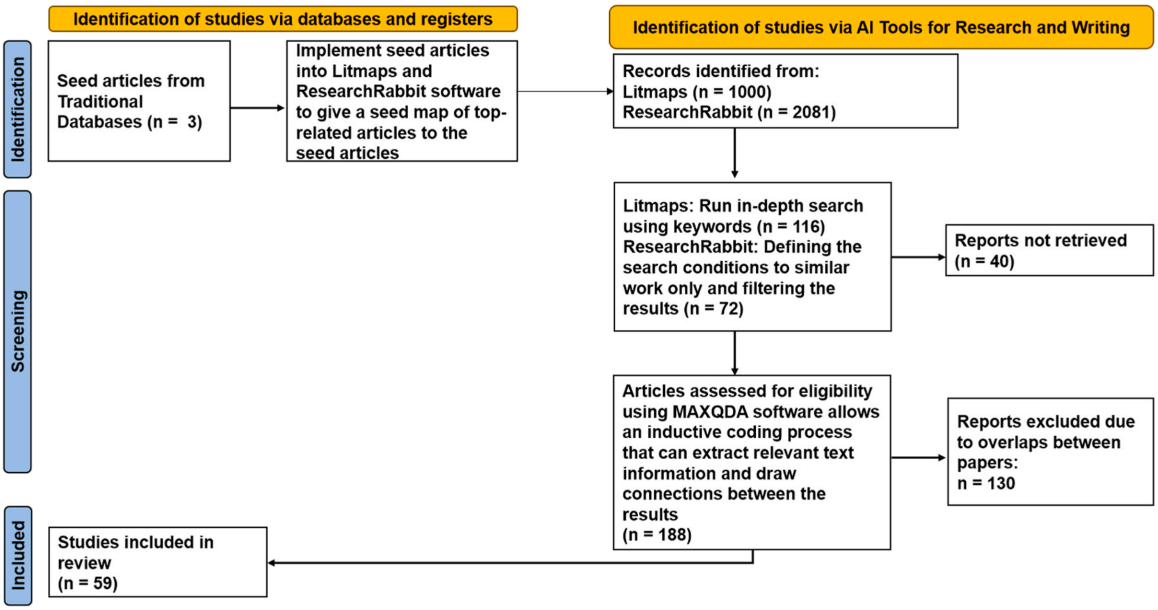

Fig. 5. PRISMA Flow Diagram Illustrating the Article Selection Criteria for the Systematic Review.

After applying in-depth search and filtering options in Litmaps and ResearchRabbit, we obtained 116 and 72 articles, respectively, that matched our specific research interests. In total, 188 articles were imported into MAXQDA software for further analysis. Through a rigorous coding process in MAXQDA, we narrowed down the articles to 59 that specifically addressed the remediation of heavy metals and PAHs in co-contaminated soil. By refining our coding segments, we aimed to answer our three specific research questions effectively using the final 59 selected articles.

The flowchart presented in the image provides an overview of the systematic process used to select relevant articles for the literature review on the remediation of heavy metals and PAHs in co-contaminated soil. The flowchart follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which are widely used for systematic reviews.

1. Identification: The process begins with the identification of relevant articles through traditional academic databases such as ERIC, JSTOR, MEDLINE, PubMed, ScienceDirect, and Google Scholar. These databases serve as the "traditional search systems" and are the primary sources for initial article selection.
2. Seed Articles: Three seed articles are selected from the traditional search systems to initiate the AI-assisted search using Litmaps and ResearchRabbit software.
3. AI-assisted Search: The Litmaps and ResearchRabbit software are used to search for highly related articles based on the seed articles. Litmaps uses data providers such as OpenAlex, Crossref, and Semantic Scholar, while ResearchRabbit uses the ORCID profile and other citation options for search.
4. Initial Search Results: The initial AI-assisted search in Litmaps yields 1000 articles, and ResearchRabbit results in 2081 articles that are potentially related to the research topic.
5. In-depth Search and Filtering: To narrow down the results and ensure relevance, an in-depth search is performed in Litmaps, and a filtering approach is applied in ResearchRabbit. These processes refine the search results to obtain 116 articles from Litmaps and 72 articles from ResearchRabbit that closely match the research interest.
6. Articles Imported into MAXQDA: The final selection of articles, 188 in total, from both traditional search systems and AI-assisted tools are downloaded and imported into the MAXQDA software for further analysis.
7. Coding and Segmentation: MAXQDA software is used for coding and segmentation of articles. The coding process involves categorizing the articles based on specific criteria related to the research questions. This step helps in identifying articles that meet the inclusion criteria and those that are relevant to the research objectives.
8. Article Refinement: Through the coding process, articles that overlap or do not specifically address the remediation of heavy metals and PAHs in co-contaminated soil are removed, leaving a refined set of 59 articles that align with the research objectives.

Overall, flow chart illustrates a comprehensive and systematic approach to selecting and analyzing relevant studies for the systematic review on the remediation of heavy metals and PAHs in co-contaminated soil, combining traditional academic database searches with AI-assisted tools for a more comprehensive analysis.

3. Results and discussion

Analyzing the Efficacy of Remediation Techniques in Co-Contaminated Soils: Interaction Mechanisms, Challenges of Combined Approaches, and Influencing Factors on Treatment Effectiveness.

3.1. Part 1 What are the interaction mechanisms between heavy metals and PAHs in contaminated soils, and how do these affect the efficacy of different remediation methods?

To better understand the different remediation approaches presented in published articles, it is crucial to gain insights into how heavy metals and PAHs compounds interact within the contaminated soil, which can influence the efficiency of remediation techniques. Thus, our first research question aims to address this issue.

The coexistence of PAHs and heavy metals in soil mediates several complex interactions, including cation-π interaction, adsorption of organic materials to minerals, and cross-linking between different components within the soil [140,148–152]. Cation-π interaction is a non-covalent interaction that occurs between an electron-rich π system of an aromatic structure and an adjacent cation. The strength of this interaction depends on the properties of the contaminants, such as their molecular weight, surface area, and number of bonds. For instance, Kim et al. demonstrated a significant cation-π interaction between nickel and benzo[*a*]anthracene, leading to increased nickel solubility in chloroform

[153]. The number of aromatic rings also affects the reaction rate, with electron-rich aromatic rings exhibiting stronger cation-π interactions [148,149]. Other factors that influence the physical and chemical state of heavy metals and PAHs in the soil include clay type and concentration, as well as organic matter content [140,150]. Interactions of heavy metals and PAHs with soil particles result in the bonding of these contaminants with different functional groups of organic matter. This bonding increases the adsorptive capability of organic matter by enhancing their Log Kow values [140,151,152,154]. The specific surface area and negative charge of clay particles in the soil contribute to their adsorption properties. The negatively charged clay surfaces adsorb positively charged heavy metals through cation exchange within the interlayers or by forming inner-sphere complexes at the edge of clay particles. This facilitates the sorption of PAHs due to their strong cation-π interactions [140,150,152,155,156]. The strong bond between PAHs and metals induces the formation of bridge structures and multi-cross-linking bonds between PAHs and soil organic matter, leading to nonlinear sorption of PAHs in the soil [157–159]. Understanding these complex interactions is essential for developing effective remediation strategies for co-contaminated soils.

Microbes play a vital role in the removal of heavy metals and the biodegradation of PAHs compounds in contaminated soil. These microorganisms have the ability to undergo various modifications in response to oxidative stress, which makes them highly adaptable and tolerant of harsh environments contaminated with pollutants soil [160]. Studies have shown that microbial activity increases in the presence of co-contaminants, particularly in soils with high salinity. Additionally, the biodegradation of certain PAHs, such as acenaphthene, fluorene, and pyrene, is more efficient when heavy metals are also present in the soil compared to phenanthrene [161]. In co-contaminated soil, where both heavy metals and petroleum hydrocarbons exist, a study found high contamination levels of C12-C17 hydrocarbons and PAHs compounds, with Indeno[1,2,3-cd]pyrene being the most abundant PAH compound. The heavy metal contamination was found to range from Zn $>$ Ni $>$ Pb $>$ As $>$ Co $>$ Cr. However, the complexity of the composition in contaminated soil warrants further investigation soil [162]. Without a comprehensive understanding of the different contributors to soil contamination, it becomes challenging, if not impossible, to implement effective remediation treatments in various contaminated sites. Therefore, gaining insights into the interactions and impacts of heavy metals and PAHs in co-contaminated soil is crucial for developing successful and sustainable remediation strategies. The integration of PAHs into the micro- or nanopores of soil organic matter during the formation of bound-residue fractions can lead to reduced bioavailability of PAHs in aged soil, raising concerns about the effectiveness of remediation methods [163]. However, another study found that the presence of high concentrations of Cu and Al in co-contaminated soil can actually increase the bioavailability of phenanthrene, suggesting that the behavior of PAHs in contaminated soil can be influenced by the presence of heavy metals [163]. The risk of heavy metal accumulation in co-contaminated soil can also have negative effects on microbial activity and the biodegradation of PAHs, as indicated by previous studies PAHs [164, 165]. The presence of multiple contaminants in the soil, such as PAHs and heavy metals, can lead to complex interactions among these pollutants and with other environmental factors, including plants and the rhizosphere [166,167]. Over the years, heavily contaminated soils have accumulated, presenting a significant challenge in finding suitable and effective remediation approaches [166]. In Conclusion, understanding the complex interplay between heavy metals and PAHs in co-contaminated soils is crucial for creating successful remediation methods. Our study uncovers key factors, such as cation-π interactions, types of clay, and organic matter content, that substantially influence how these contaminants behave in the soil. Microorganisms stand out as critical agents, showing resilience in adverse conditions and aiding in the elimination of heavy metals and the breakdown of PAHs. Yet, the coexistence of diverse contaminants adds layers of complexity, affecting both microbial performance and remediation efficiency.

3.2. Part 2: What are the challenges and limitations of combined remediation techniques for co-contaminated soils compared to single-treatment methods in terms of efficiency, stability, and specificity?

To address this question, we conducted an in-depth analysis of various studies presented in Table 3. Herein, we conducted a comprehensive comparison of different treatment methodologies and experimental conditions employed in the published articles discussed within this study. The table is composed of several columns, each providing specific information about the treatments and experimental setups. The "Type of Treatment" column indicates whether the treatment is implemented as a single approach or as a combination of multiple methods. The "Sub-Type of Treatment" column further specifies the combination of treatment methodologies used in the studies. In the "Plant" section, the type of plant species utilized in each study is listed. The "Microbes" section identifies the specific microorganisms applied in the treatment processes. The "Amendments" section lists the components added to the soil to facilitate the remediation process. The types of polycyclic aromatic hydrocarbons (PAHs) targeted for remediation are detailed in the corresponding column. The "Heavy Metal" column specifies the specific heavy metals targeted for remediation in each study. The "Source of Soil" column indicates the origin or contamination source of the soil used in the respective experiments. Finally, the "Lab or Field" column distinguishes whether the experiments were conducted in laboratory settings or in real field environments. These parameters collectively provide valuable insights into the most studied aspects of remediation technologies for co-contaminated soils with PAHs and heavy metals.

3.2.1. Categorization of remediation methods: diverse approaches and their sub-types

The analysis of published articles presented in Table 3 and Fig. 6 provides valuable insights into the distribution of single and combined treatment methodologies used in the remediation of co-contaminated soils with heavy metals and PAHs. The results indicate that while a substantial portion (25%) of the studies focused on employing a single treatment approach, the majority of researchers (75%) opted for a combination of treatment strategies (Figs. 6a and 6b). Biological approaches emerged as the most commonly used treatment method in the single treatment category, highlighting the significance of utilizing microbial and plant-based techniques in addressing co-contamination challenges. These biological approaches have proven to be effective in mitigating the presence of heavy metals and PAHs in contaminated soils. However, the prevalence of combined treatment approaches indicates their greater popularity and effectiveness in dealing with the complexities of co-contaminated soils.

Among the combined treatments, the combination of biological-biological approaches stood out as the most favored and frequently explored method (Fig. 6b). This reflects the recognition of the synergistic benefits obtained by employing multiple biological techniques simultaneously. Further analysis of different categories of combined treatments revealed interesting trends in their usage. The most frequently tested combined treatment approach was biostimulation-bioaugmentation, which constituted 22% of the studies. This combination involves stimulating the natural biological processes in the soil while also introducing specific microorganisms to enhance the remediation process. Following closely behind, biostimulation-phytoremediation and bioaugmentation-phytoremediation accounted for 20% and 5% of the combined treatments, respectively. These approaches leverage the power of plant-based remediation along with biostimulation or bioaugmentation techniques. A smaller proportion (8%) of studies explored several combinations of biological treatments, such as biostimulation-bioaugmentation-phytoremediation and bioventing-biosparging-phytoextraction, indicating the interest in comprehensive and integrated remediation approaches. Additionally,

Table 3
Comparison of Different Treatment Methodologies and Experimental Conditions in Published Articles Discussed in the Study.

	Type of Treatment Methodology			Components of Treatment (ex. name of chemicals, microorganisms, physical) with their concentrations			Type of PAHs and Heavy Metals		Experimental Conditions		References
No.	Single or Combined	Type of Treatment	Sub-Type of Treatment	Plant	Microbes	amendments	PAHs	Heavy metal	Source of Soil	Lab or Field	
1	Combined	Biological-Biological-Biological	Biostimulation-Bioaugmentation-Phytoremediation	*Solanum nigrum L.* *Medicago sativa L.*	*Bacillus sp.* *Saccharomyces sp.* *Micrococcus sp.*	β-CD, rice husk, biochar, calcium magnesium phosphate fertilizer, organic fertilizer	Acenaphthene Acenaphthylene Anthracene Fluoranthene Fluorene Naphthalene Phenanthrene Pyrene Benz[*a*] anthracene Benzo [*b*]fluoranthene Bnzo[*k*] fluoranthene Benzo[ghi] perylene benzo[*a*] pyrene chrysene Dibenz[*a*, *h*] anthracene Indeno[1,2,3-cd]	Cd, Pb, Zn	Industrial contaminated site	lab	[125]
2	Combined	Biological-Biological	Biostimulation-Phytoremediation	*Solanum lycopersicum, Hordeum sativum Distichum*		Biochar obtained from sunflower husks	Benzo[*a*]pyrene	Cu	Induced contamination	Lab	[168]
3	Combined	Biological-Biological-Biological	Bioventing-Biosparging-Phytoextraction	*Brassica juncea*			Pyrene	Pb	Industrial contaminated site	Field	[34]
4	Combined	Chemical-Biological	Chemical-Phytoremediation	*Solanum nigrum*		EDTA, cysteine, salicylic acid, Tween 80	Acenaphthene Acenaphthylene Anthracene Fluoranthene Fluorene Naphthalene Phenanthrene Pyrene Benz[*a*] anthracene Benzo [*b*]fluoranthene Bnzo[*k*] fluoranthene Benzo[ghi] perylene benzo[*a*] pyrene chrysene Dibenz[*a*, *h*] anthracene Indeno[1,2,3-cd]	Cd	Agricultural site contaminated with sewage irrigation	Lab	[169]
5	Combined	Biological-Biological	Biostimulation-Bioaugmentation		*Pleurotus cornucopiae* *Bacillus thuringiensis*		Phenanthrene	Cd	Induced contamination	lab	[164]
6	Combined	Biological-Biological	Biostimulation-Phytoremediation	*Robinia pseudoacacia*	Gram-negative bacteria *Actinomycetes*	biochar, gravel sludge, iron oxides	Acenaphthene Acenaphthylene Anthracene Fluoranthene Fluorene Naphthalene	As, Cu, Cd, Pb, Zn	Industrial site	Lab	[170]

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Table 3 (*continued*)

	Type of Treatment Methodology			Components of Treatment (ex. name of chemicals, microorganisms, physical) with their concentrations			Type of PAHs and Heavy Metals		Experimental Conditions		References
No.	Single or Combined	Type of Treatment	Sub-Type of Treatment	Plant	Microbes	amendments	PAHs	Heavy metal	Source of Soil	Lab or Field	
							Phenanthrene Pyrene Benz[*a*] anthracene Benzo [*b*]fluoranthene Bnzo[*k*] fluoranthene Benzo[ghi] perylene benzo[*a*] pyrene chrysene Dibenz[*a*, *h*] anthracene Indeno[1,2,3-cd]				
7	Combined	Chemical-Chemical	Chemical-Biostimulation			Eethylenedinitrilo-tetraacetic acid disodium salt (Na-EDTA), polyethylene glycol dodecyl ether (Brij® 35 P), polyethylene glycol sorbitan monooleate (Tween® 80).	Phenanthrene	Pb	Industrial site	Lab	[58]
8	Combined	Biological-Biological	Biostimulation-Bioaugmentation		*Escherichia sp.*	Biochar	Pyrene	Cd	Industrial site	lab	[171]
9	Combined	Biological-Biological	Biostimulation-Phytoremediation	*Medicago sativa L.* *Pisum sativum* *Zea mays*	Earthworms	Compost was purchased (drk sphagnum, lys sphagnum, zeolite)	Acenaphthene Acenaphthylene Anthracene Fluoranthene Fluorene Naphthalene Phenanthrene Pyrene Benz[*a*] anthracene Benzo [*b*]fluoranthene Bnzo[*k*] fluoranthene Benzo[ghi] perylene benzo[*a*] pyrene chrysene Dibenz[*a*, *h*] anthracene Indeno[1,2,3-cd]	Pb, Co, As, Mn	Industrial site	Lab	[172]
10	Combined	Physical-Chemical	Chemical-Electrokinetics			EDTA,Tween 80	Acenaphthene Acenaphthylene Anthracene Fluoranthene Fluorene Naphthalene Phenanthrene Pyrene Benz[*a*] anthracene Benzo [*b*]fluoranthene Bnzo[*k*] fluoranthene Benzo[ghi]	As, Cd, Cr, Cu, Ni, Pb	Industrial site	Lab	[173]

(*continued on next page*)

Table 3 (*continued*)

No.	Type of Treatment Methodology			Components of Treatment (ex. name of chemicals, microorganisms, physical) with their concentrations			Type of PAHs and Heavy Metals		Experimental Conditions		References
	Single or Combined	Type of Treatment	Sub-Type of Treatment	Plant	Microbes	amendments	PAHs	Heavy metal	Source of Soil	Lab or Field	
							perylene benzo[*a*]pyrene chrysene Dibenz[*a*, *h*]anthracene Indeno[1,2,3-cd]				
11	Combined	Biological-Biological	Biostimulation-Phytoremediation	*Solanum nigrum L.*		Cysteine, EDTA, salicylic acid, Tween 80	Benzo[*a*]pyrene	Cd	Induced contamination	Lab	[174]
12	Combined	Biological-Biological	Biostimulation-Bioaugmentation	*Festuca L.* *Echinacea purpurea L.*	*Mycobacterium strain N12*		Pyrene Chrysene Benzo[*b*]fluoranthene Benzo[*k*]fluoranthene	Cd	Oil Field	Lab	[175]
13	Combined	Physical-Chemical	Chemical-Flushing			Deionized water, EDTA, surfactant (Igepal), hydroxypropyl-β-cyclodextrin	Phenanthrene Pyrene Benzo[*a*]pyrene	Co, Pb, Zn	Manufactured Gas Plant	Field	[59]
14	Combined	Physical-Chemical	Chemical-Washing			carboxymethyl-β-cyclodextrin, carboxymethyl chitosan	Acenaphthene Acenaphthylene Anthracene Fluoranthene Fluorene Naphthalene Phenanthrene Pyrene Benz[*a*]anthracene Benzo[*b*]fluoranthene Bnzo[*k*]fluoranthene Benzo[ghi]perylene benzo[*a*]pyrene chrysene Dibenz[*a*, *h*]anthracene Indeno[1,2,3-cd]	Pb, Cd, Cr, Ni	Metallurgic plant	Lab	[60]
15	Combined	Biological-Biological	Biostimulation-Phytoremediation	*Festuca L.*			Pyrene, chrysene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene	Cd	Oil Field	Lab	[176]
16	Combined	Physical-Biological	Flushing-Biostimulation			Rhamnolipid	Phenanthrene	Cd	Induced contamination	Lab	[177]
17	Combined	Biological-Biological	Biostimulation-Bioaugmentation		*Pleurotus eryngii mycelium*	Tween 80, saponin	Phenanthrene	Mn	Induced contamination	Lab	[178]
18	Combined	Biological-Biological	Biostimulation-Phytoremediation	*Medicago sativa L.*			Acenaphthene Acenaphthylene Anthracene Fluoranthene Fluorene Naphthalene Phenanthrene Pyrene Benz[*a*]	Cd	Landfill site	Lab	[179]

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Table 3 (*continued*)

	Type of Treatment Methodology			Components of Treatment (ex. name of chemicals, microorganisms, physical) with their concentrations			Type of PAHs and Heavy Metals		Experimental Conditions		References
No.	Single or Combined	Type of Treatment	Sub-Type of Treatment	Plant	Microbes	amendments	PAHs	Heavy metal	Source of Soil	Lab or Field	
							anthracene Benzo[*b*]fluoranthene Bnzo[*k*] fluoranthene Benzo[ghi] perylene benzo[*a*] pyrene chrysene Dibenz[*a*, *h*] anthracene Indeno[1,2,3-cd]				
19	Combined	Biological-Biological-Biological	Biostimulation-Bioaugmentation-Phytoremediation	*Sedum alfredii*	*Ochrobactrum intermedium B [a]P-16*	Saponin	Benzo[*a*]pyrene	Cd	Induced contamination	Lab	[180]
20	Combined	Biological-Biological	Biostimulation-Phytoremediation	*Cpm1 (Enterobacter cloacae HS32, Brevibacillus reuszeri HS37, and Stenotrophomonas sp. HS16) and Cpm2 (Acinetobacter junii HS29, Enterobacter aerogenes HS39 and Enterobacter asburiae HS22).*	*Enterobacter cloacae, Brevibacillus reuszeri, Stenotrophomonas sp., Acinetobacter junii, Enterobacter aerogenes, Enterobacter asburiae*	Biochar	Phenanthrene, anthracene, pyrene, benzo[*a*] pyrene	Cr, Ni, Pb	Oil field	Lab	[181]
21	Combined	Physical-Chemical-biological	Ultrasound-Chemical-bioaugmentation		*Mycobacterium spp. MB1, Microbacterium sp. KL5, and Rhodococcus sp. R2.*	methyl-b-cyclodextrin, SS-ethylenediaminedisuccinic acid	Acenaphthene Acenaphthylene Anthracene Fluoranthene Fluorene Naphthalene Phenanthrene Pyrene Benz[*a*] anthracene Benzo[*b*]fluoranthene Bnzo[*k*] fluoranthene Benzo[ghi] perylene benzo[*a*] pyrene chrysene Dibenz[*a*, *h*] anthracene Indeno[1,2,3-cd]	Cu, Cr, Zn, As, Pb, Cd, Ni, K	Manufactured Gas Plant site	Lab	[182]
22	Combined	Physical-Biological	Biostimulation-Flushing			Rhamnolipid, sophorolipid	Phenanthrene	Pb	Induced contamination	Lab	[183]
23	Combined	Physical-Physical	Electrokinetic-Ultrasonic				Phenanthrene	Pb	Induced contamination	Lab	[184]
24	Combined	Biological-Biological	Bioagumentation-Phytoremediation	*Sedum alfredii*	*Burkholderia cepacia*		Phenanthrene	Pb, Zn	Mine site	Lab	[185]
25	Combined	Biological-Biological	Bioaugmentation-Phytoremediation		*Klebsiella pneumoniae*		Pyrene	Ni	Induced contamination	Lab	[186]
26	Combined	Biological-Biological	Bioaugmentation-Bioaugmentation		Formulated consortia *Cpm1 (Enterobacter cloacae HS32, Brevibacillus reuszeri HS37,*		Fluoranthene	Ni	Industrial site	Lab	[187]

(*continued on next page*)

Table 3 (*continued*)

	Type of Treatment Methodology			Components of Treatment (ex. name of chemicals, microorganisms, physical) with their concentrations			Type of PAHs and Heavy Metals		Experimental Conditions		References
No.	Single or Combined	Type of Treatment	Sub-Type of Treatment	Plant	Microbes	amendments	PAHs	Heavy metal	Source of Soil	Lab or Field	
					and Stenotrophomonas sp. HS16) and Cpm2 (Acinetobacter junii HS29, Enterobacter aerogenes HS39 and Enterobacter asburiae HS22).						
27	Combined	Biological-Biological	Biostimulation-Bioaugmentation		Undefined consortia	Monoammonium phosphate	Benzo[*a*] anthracene	Cu	Induced contamination	Lab	[188]
28	Combined	Biological-Biological	Biostimulation-Bioaugmentation			Potassium phosphate, sodium nitrate	Phenanthrene	Cu	Induced contamination	Lab	[164]
29	Combined	Biological-Biological	Biostimulation-Bioaugmentation		*Enterobacter cloacae, Brevibacillus reuszeri, Stenotrophomonas sp., Acinetobacter junii, Enterobacter aerogenes, Enterobacter asburiae*	Biochar	Total PAHs	Pb, Cr, Ni	Oil spill site	Lab	[181]
30	Combined	Biological-Biological	Biostimulation-Bioaugmentation		*Actinobacteria sp., Proteobacteria sp., Bacteroidetes sp., Arachidicoccus sp., Sphingobium sp.*	Dichondra repens	Phenanthrene	Cu	Induced contamination	Lab	[189]
31	Combined	Biological-Biological	Biostimulation-Phytoremediation	*Helianthus annuus L.*		Modified rice straw	Phenanthrene	Cd	Induced contamination	Lab	[155]
32	Combined	Biological-Biological	Biostimulation-Bioaugmentation			Spent mushroom compost	Total PAHs	Pb	Industrial site	Lab	[190]
33	Combined	Biological-Biological	Biostimulation-Phytoremediation	*Megathyrsus maximus*		Spent mushroom compost	Total PAHs	HM	Oil spill site	Lab	[191]
34	Combined	Physical-Biological	Biostimulation-Washing			Methylglycinediacetic acid, Alkyl glucoside	Total PAHs	As	Industrial site	Lab and Field	[192]
35	Combined	Biological-Biological	Biostimulation-Phytoremediation	*Pomatoceros triqueter*		Citric acid, succinic acid, glutaric acid	Pyrene	Pb	Induced contamination	Lab	[154]
36	Combined	Biological-Biological	Biostimulation-Bioaugmentation		*Pseudomonas sp. ASDP1, Burkholderia sp. ASDP2, and Rhodococcus sp. ASDP3.*	Cetyl tri-methyl ammonium bromide, sodium dodecyl sulfate, Tween 80, Triton X-100	Pyrene	HM	Induced contamination	Lab	[193]
37	Combined	Biological-Biological	Biostimulation-Bioaugmentation		*Bacillus (JN897279) and Pseudomonas (KJ541832)*	Rhamnolipid	Pyrene Phenanthrene Benzo[*a*]pyrene	HM	Induced contamination	Lab	[10]
38	Combined	Physical-Biological	Flushing-Biostimulation			Rhamnolipid, sophorolipid	Phenanthrene	Pb	Induced contamination	Lab	[183]
39	Combined	Physical-Biological	Electrokinetics-Biostimulation			Tween-20	Total PAHs	HM	Induced contamination	Lab	[194]
40	Combined	Physical-Biological	Biostimulation-Washing			Rhamnolipid	Phenanthrene	Cd	Induced contamination	Lab	[177]
41	Combined	Biological-Biological	Bioaugmentation-Phytoremediation	*Medicago sativa L.*	*Piriformospora indica*		Phenanthrene	Cd	Induced contamination	Lab	[195]
42	Combined	Biological-Biological	Biostimulation-Phytoremediation	*Brassica juncea, Salix viminalis, and Festuca arundinacea*		EDTA	Acenaphthene Acenaphthylene Anthracene Fluoranthene Fluorene	Cu, Pb, Zn	Industrial site	Lab	[196]

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Table 3 (*continued*)

No.	Type of Treatment Methodology			Components of Treatment (ex. name of chemicals, microorganisms, physical) with their concentrations			Type of PAHs and Heavy Metals		Experimental Conditions		References
	Single or Combined	Type of Treatment	Sub-Type of Treatment	Plant	Microbes	amendments	PAHs	Heavy metal	Source of Soil	Lab or Field	
							Naphthalene Phenanthrene Pyrene Benz[*a*] anthracene Benzo [*b*]fluoranthene Bnzo[*k*] fluoranthene Benzo[ghi] perylene benzo[*a*] pyrene chrysene Dibenz[*a*, *h*] anthracene Indeno[1,2,3-cd]				
43	Single	Physical	Calcination Treatment				Naphthalene Fluoranthene	Zn, Cu	Industrial contaminated site	Lab	[197]
44	Single	Biological	Phytoremediation	*Brassica juncea*			Pyrene	Cu	Induced contamination	Lab	[198]
45	Single	Biological	Phytoextraction	*Halimione portulacoides*			Acenaphthene Acenaphthylene Anthracene Fluoranthene Fluorene Naphthalene Phenanthrene Pyrene Benz[*a*] anthracene Benzo [*b*]fluoranthene Bnzo[*k*] fluoranthene Benzo[ghi] perylene benzo[*a*] pyrene chrysene Dibenz[*a*, *h*] anthracene Indeno[1,2,3-cd]	Cu	Induced contamination	Lab	[166]
46	Single	Biological	Bioaugmentation		*Pseudomonas gessardii strain LZ-E*		Naphthalene	Cr	Industrial contaminated site	lab	[199]
47	Single	Biological	Bioremediation		Undefined consortia		Total PAHs	Pb, Zn, Cu, Cr, Co, Cd, Ni, Hg, As, Ba	Industrial contaminated site	Lab	[200]
48	Single	Biological	Bioaugmentation		*Bacillus sp. strain KC5, Pseudomonas sp. strain KC3, Pseudomonas (MTS-1), Stenotrophomonas (MTS-2), Agrobacterium (MTS-4), Trabulsiella (MTS-6),* and *Cupriavidus (MTS-7)*		Acenaphthene, Phenanthrene Anthracene Fluoranthene Pyrene Benzo[*a*] anthracene	Cd, Pb, Co, Zn	Industrial contaminated site	Lab	[201]

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Table 3 (*continued*)

	Type of Treatment Methodology			Components of Treatment (ex. name of chemicals, microorganisms, physical) with their concentrations			Type of PAHs and Heavy Metals		Experimental Conditions		References
No.	Single or Combined	Type of Treatment	Sub-Type of Treatment	Plant	Microbes	amendments	PAHs	Heavy metal	Source of Soil	Lab or Field	
							Benzo[*k*] fluoranthene				
49	Single	Physical	Electrokinetic system				Phenanthrene	Ni	Induced contamination	Lab	[202]
50	Single	Biological	Phytoremediation	*Sorghum*		Leachate	Pyrene	Pb, Cd	Landfill site	Lab	[203]
51	Single	Biological	Biostimulation			Arquad® 2HT-75, palmitic acid	Phenanthrene	Cd	Industrial site	Lab and Field	[204]
52	Single	Biological	Biostimulation			Saponin, Triton X100	Phenanthrene	Cd	Induced contamination	Lab	[205]
53	Single	Biological-Biological	Biostimulation-Phytoremediation	Grasses Plugs Trees Shrubs			Acenaphthene Acenaphthylene Anthracene Fluoranthene Fluorene Naphthalene Phenanthrene Pyrene Benz[*a*] anthracene Benzo [*b*]fluoranthene Bnzo[*k*] fluoranthene Benzo[ghi] perylene benzo[*a*] pyrene chrysene Dibenz[*a*, *h*] anthracene Indeno[1,2,3-cd]	Sb, As, Ba, Be, Cd, Cr, Co, Pb, Mn, Ni, Se, Th, V	Industrial Site	Field	[206]
54	Single	Biological	Biostimulation			β-CDs	Anthracene	Cd	Induced contamination	Lab	[207]
55	Single	Biological	Phytoremediation	*Oryza sativa L.*			Total PAHs	Cd, As	Induced contamination	Lab	[208]
56	Single	Biological	Phytoremediation	*Cannabis sativa L.*			Phenanthrene Pyrene	Cu	Induced contamination	Lab	[209]

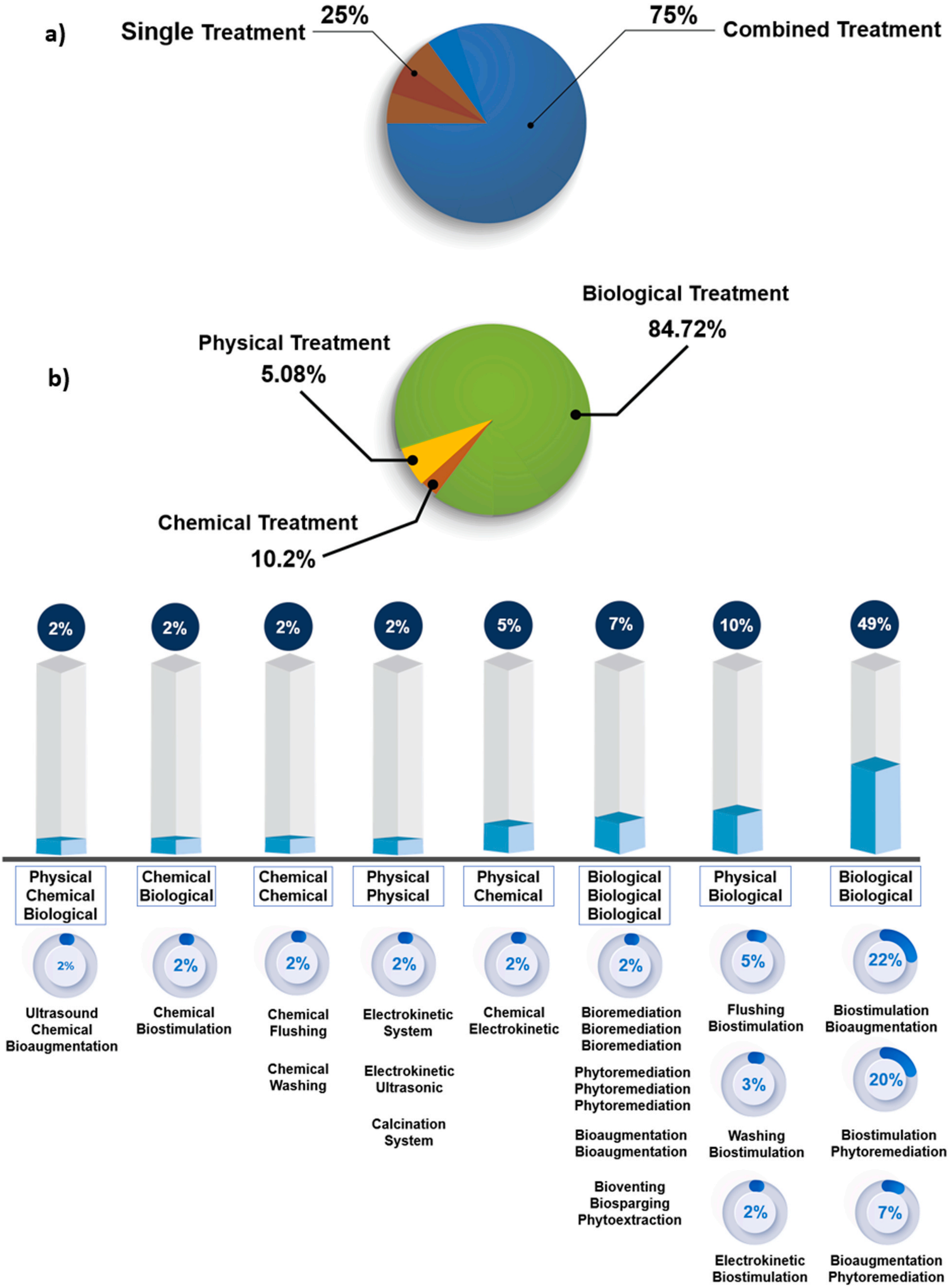

Fig. 6. The different types of remediation approaches that were used in published articles. (a) Represents the percentage of single treatments compared to combined treatments. (b) Represents the types of remediation approaches and their sub-categories.

15% of the published studies combined biological treatments with other types of treatments. These combinations included flushing-biostimulation, washing-biostimulation, electrokinetic-biostimulation, chemical-biostimulation, chemical-phytoremediation, and ultrasound-chemical-bioaugmentation. This highlights the diversity and creativity in devising hybrid treatment strategies to address the complexity of co-contaminated soils. In contrast, physical treatments accounted for approximately 6% of the studies, with electrokinetic systems, electrokinetic-ultrasonic approaches, and calcination systems being the most commonly tested physical treatment methods. Additionally, physical treatments were combined with chemical treatment in the form of a chemical-electrokinetic system, showcasing the potential for synergy between different remediation techniques. It is worth noting that chemical treatment through the application of the Chemical-Washing system was the least commonly used approach, representing only 2% of the studies. This could be attributed to its limitations and challenges in stabilizing heavy metals and degrading PAHs in co-contaminated soils. Thus, the data presented in Fig. 6b provides valuable insights into the preferences and trends in combined treatment methodologies for co-contaminated soils. These findings underscore the importance of incorporating various biological approaches into combined treatment strategies, as they have shown promising results in enhancing the efficiency and efficacy of remediation efforts. Understanding the distribution and effectiveness of different remediation techniques in co-contaminated soils can serve as a valuable reference for future research and the development of more sustainable and comprehensive remediation strategies. As environmental concerns continue to grow, these insights can play a pivotal role in advancing the field of soil remediation and ensuring the restoration of contaminated environments.

In the selected papers, a clear emphasis was observed on the degradation of phenanthrene, followed by pyrene, compared to other PAH compounds (Fig. 7b). Similarly, with regard to heavy metals, the majority of studies focused on the removal of Pb and Cd from contaminated soils (Fig. 7a). The extensive investigation of phenanthrene and pyrene, along with Pb and Cd, can be attributed to their high abundance in contaminated soils [210–212]. Additionally, the unique chemical structures of phenanthrene and pyrene make them particularly attractive for biodegradation studies [211]. Phenanthrene is composed of three fused rings arranged in an angular manner, while pyrene consists of four fused benzene rings in a clustered arrangement. Both compounds have two aromatic π-sextets. However, during transformation reactions, phenanthrene loses one π-sextet, while pyrene loses all of its π-sextets. As a result, pyrene becomes more readily utilized by microorganisms as a sole carbon source for energy production, making it more prone to biodegradation than phenanthrene [213,214]. The high prevalence of phenanthrene and pyrene, along with Pb and Cd, in the published articles on remediation studies is reflective of their significance as the most studied parameters. These findings underscore the importance of understanding the behavior and remediation potential of these specific compounds and heavy metals in contaminated soils (Fig. 7). Further research on the degradation of other PAH compounds and the removal

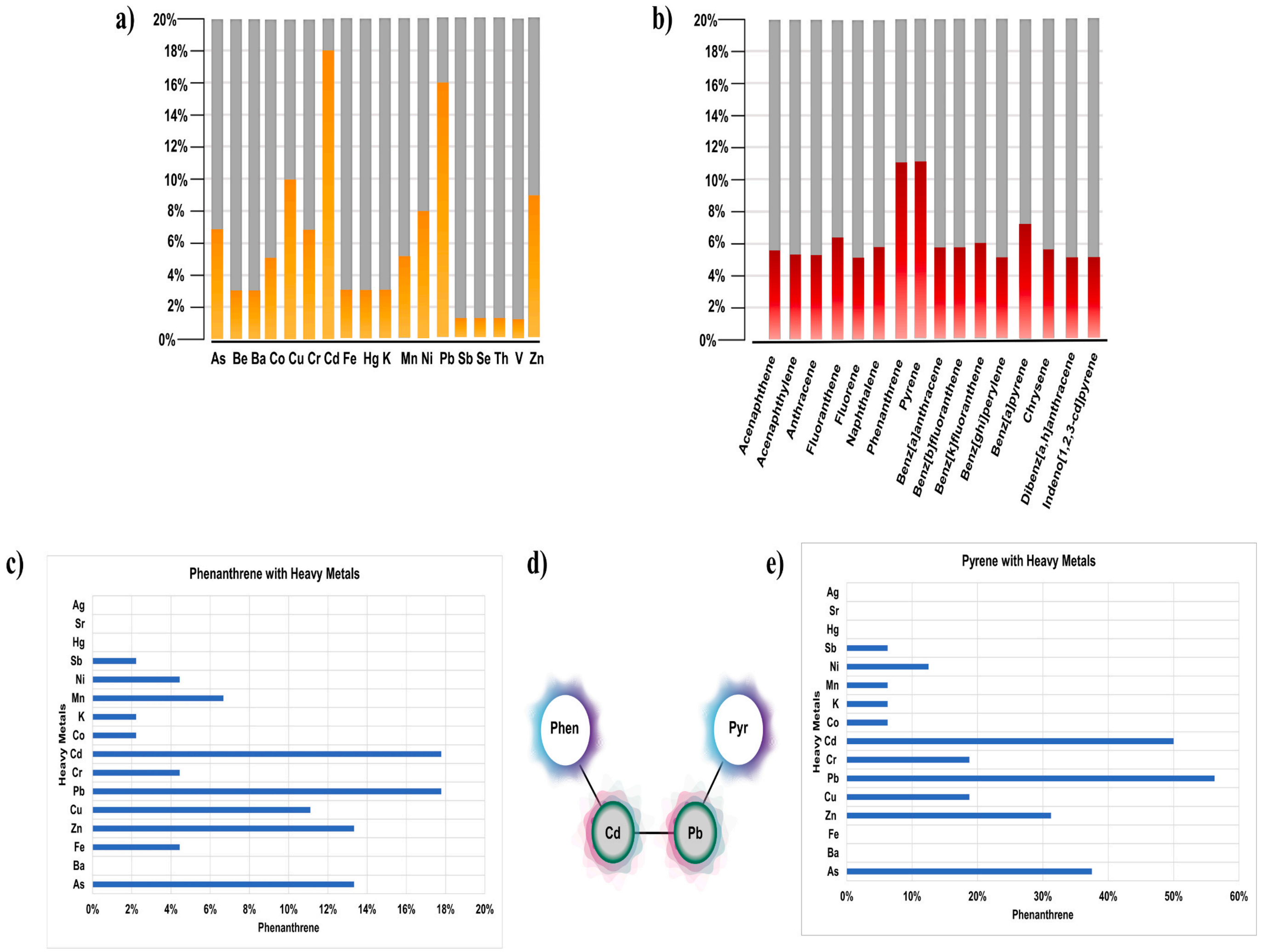

Fig. 7. The percentage distribution of heavy metals with (c) phenanthrene and (e) pyrene in published articles. (d) Most studied PAHs and Heavy Metals.

of different heavy metals can contribute to a more comprehensive understanding of remediation technologies and expand the scope of effective strategies for addressing co-contaminated environment.

3.2.2. Distribution of microorganisms and plant species in reviewed literature

Biological treatments, involving the use of microbes and plants, have garnered significant attention for remediating oil-contaminated soils. A diverse range of 58 microbial strains have been isolated and studied for their ability to detoxify co-contaminated soils with heavy metals and PAHs (Fig. 8a). Notably, bacterial species such as *Bacillus sp., Enterobacter sp.,* and *Pseudomonas sp.* are among the top isolated microbes from oil-contaminated soil and have shown a high tendency to remove Cd, Zn, and Pb, as well as degrade phenanthrene and pyrene [154,163,171,178,181,183,189–194,201,204,205,215]. *Bacillus* and *Pseudomon*as have shown remarkable capabilities to remove toxic materials from soil under extreme conditions, including pH levels ranging from 2 to 12, high temperatures up to 80 °C, and high salinity of up to 20 g/L. These microbes can simultaneously produce enzymes, such as lipase, protease, and amylase, which efficiently degrade PAHs in soils co-contaminated with heavy metals (Cd, Cu, Pb, and Zn) [10]. This suggests that these bacteria belong to the indigenous PAHs-degrading microorganisms [199,216,217]. Following the enzyme-mediated degradation processes, microbe-plant interaction plays a crucial role in the soil. Microbes contribute to the degradation of toxic compounds and assimilate nutrients, while plants help in the elimination, detoxification, metabolism, and immobilization of different toxic materials in their tissues [218]. This microbe-plant collaboration enhances the overall efficiency of remediation in co-contaminated soils.

In phytoremediation studies, a total of 44 plant species have been utilized. Among these, *Medicago sativa L.* and *Solanum nigrum L.* are the most commonly used plant species for stabilizing heavy metals and removing PAHs compounds (Fig. 8b). *Medicago sativa L.*, also known as alfalfa, is favored by many researchers due to its fast growth rate and large root system, enabling it to penetrate deep into the soil. Additionally, these plants exhibit strong tolerance to both PAHs and heavy metals [172]. *Medicago sativa L.* has demonstrated effectiveness in degrading a wide range of PAHs compounds, including naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, chrysene, benz[*a*]anthracene, benz[*k*]fluoranthene, benz[*b*]fluoranthene, benz[*a*]pyrene, indeno[1,2,3-cd]pyrene, dibenz[*a*,*h*]anthracene, and benz[ghi]perylene. Moreover, it exhibits a high capability of extracting, transferring, and stabilizing various heavy metals, including Cd, Pb, Zn, Pb, Co, As, and Mn in co-contaminated soils [125,172,179,219]. Similarly, *Solanum nigrum L.*, also known as black nightshade, is known for its high biomass production, rapid growth, and remarkable tolerance to PAHs and heavy metal contaminants in soil [125,168,169]. This plant species exhibits the ability to remove naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, chrysene, benz[*a*]anthracene, benz[*k*]fluoranthene, benz[*b*]fluoranthene, benz[*a*]pyrene, indeno[1,2,3-cd]pyrene, and dibenz[*a*,*h*]anthracene from contaminated soils. Furthermore, it shows a high tendency to stabilize and absorb Cd, Pb, and Zn in co-contaminated soils containing PAHs compounds [125,169,174]. These properties make *Medicago sativa L.* and *Solanum nigrum L.* promising candidates for phytoremediation efforts in co-contaminated soils.

3.2.3. Enhancing phytoremediation: substrate biostimulation in plant-assisted cleanup of soils co-contaminated with heavy metals and PAHs in reviewed literature

In remediation efforts for co-contaminated soils with heavy metals and PAHs, researchers have explored the use of various substrates to biostimulate plant growth and enhance their efficiency and tolerance. Among the 72 types of substrates examined, three main categories stand out: carbon substrates, plant nutrients, and organic amendments (Fig. 9). One prominent substrate used in this context is biochar, a stable carbon compound produced through the decomposition of organic material via heating in the absence of oxygen. Biochar offers a cost-effective solution compared to other carbon sources and has been widely studied for its unique characteristics and functional capacity [125,168,170,171,181]. Its ability to promote plant growth and enhance microbial activity makes it an attractive soil amendment in remediation strategies [220]. By exploring these different substrates, researchers aim to improve the overall efficiency of phytoremediation processes and the plants' ability to cope with co-contamination in soil, ultimately contributing to more effective and sustainable remediation approaches.

The extensive studies on biochar have highlighted its remarkable ability to enhance the remediation process of heavy metals and PAHs compounds, which can be attributed to its high surface area and large pore size [221,222]. As a result, biochar stands out as the most widely investigated substrate among all the examined articles. Researchers have also explored the combination of biochar with other substrates, such as gravel sludge, iron oxides, β-CD, rice husk, calcium-magnesium-phosphate fertilizer, and organic fertilizer. The efficiency of biochar, either used alone or in combination with these other substrates, has been evaluated in degrading a wide variety of PAHs, including naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, chrysene, benz[*a*]anthracene, benz[*k*]fluoranthene, benz[*b*]fluoranthene, benz[*a*]pyrene, indeno[1,2,3-cd]pyrene, dibenz[*a*,*h*]anthracene, and benz[ghi]perylene. These experiments were conducted in the presence of several heavy metals, such as Pb, Cr, Cd, Zn, Cu, Mn, and Ni.

The non-ionic surfactant Tween 80 has also been investigated for its potential in removing heavy metals and PAHs from contaminated soils [58,169,173,178,221]. Its more neutral nature compared to anionic and cationic surfactants makes it less threatening to microorganisms. Tween 80 is often used in conjunction with chelating agents like EDTA, which further enhances the removal rate of different heavy metals and PAHs in soils, particularly phenanthrene and pyrene, and Cd and Pb [58,169,173,174]. These studies shed light on the potential of biochar and Tween 80 as valuable tools in the bioremediation of co-contaminated soils, offering promising strategies for more efficient and sustainable remediation practices.

In conclusion, our comprehensive analysis of published studies highlights the prevailing trends and methodologies in the remediation of co-contaminated soils with heavy metals and PAHs. A substantial majority of the research community (75%) favors combined treatment approaches, with biological treatments being the most commonly employed method. Specifically, biostimulation-bioaugmentation combinations have garnered considerable attention due to their effectiveness in complex soil environments. Our findings also underscore the emphasis on certain PAH compounds and heavy metals, such as phenanthrene, pyrene, Pb, and Cd, which are most commonly studied due to their prevalence in contaminated soils. This points to a need for broader research that encompasses other contaminants to provide a more holistic understanding of remediation technologies. Microbial strains like *Bacillus sp.*, *Enterobacter sp.*, and *Pseudomonas sp.*, as well as plant species like Medicago sativa L. and Solanum nigrum L., have proven to be promising candidates for bioremediation. These biological agents not only demonstrate high tolerance to contaminants but also possess unique enzymatic capabilities that enhance remediation efficacy. In terms of substrates used for biostimulation, biochar stands out for its cost-effectiveness and high functional capacity, including its ability to enhance microbial activity and promote plant growth. Additionally, the non-ionic surfactant Tween 80 has been identified as a potential adjunct to chelating agents like EDTA for more effective heavy metal and PAH removal. Overall, our analysis serves as a valuable reference for future research, pointing to the necessity of integrated and innovative strategies that can tackle the complexities of co-contaminated soils. As environmental concerns escalate, these insights are pivotal for advancing soil remediation methods and ensuring effective restoration of

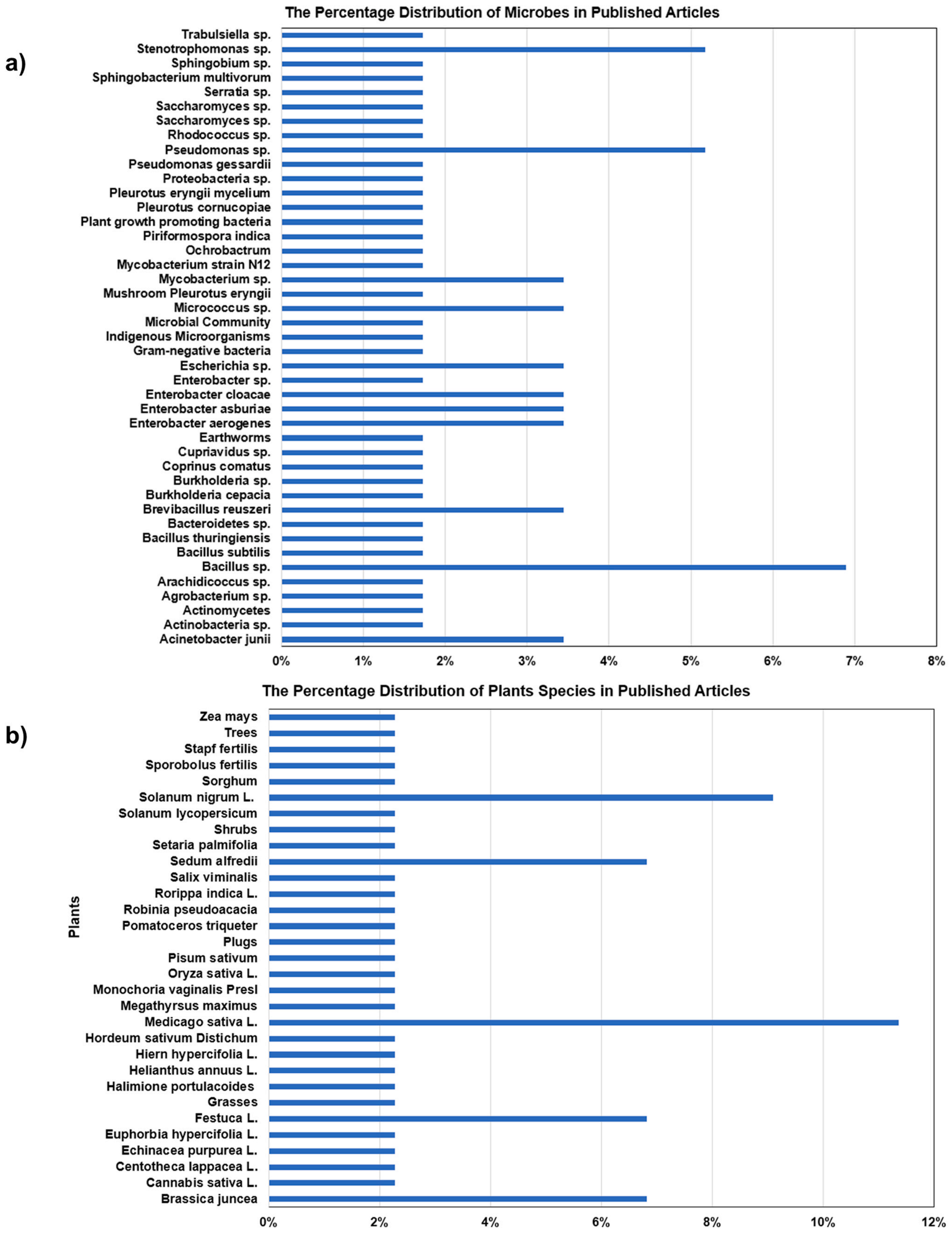

Fig. 8. The percentage distribution of different species of (a) microbes and (b) plants in published articles.

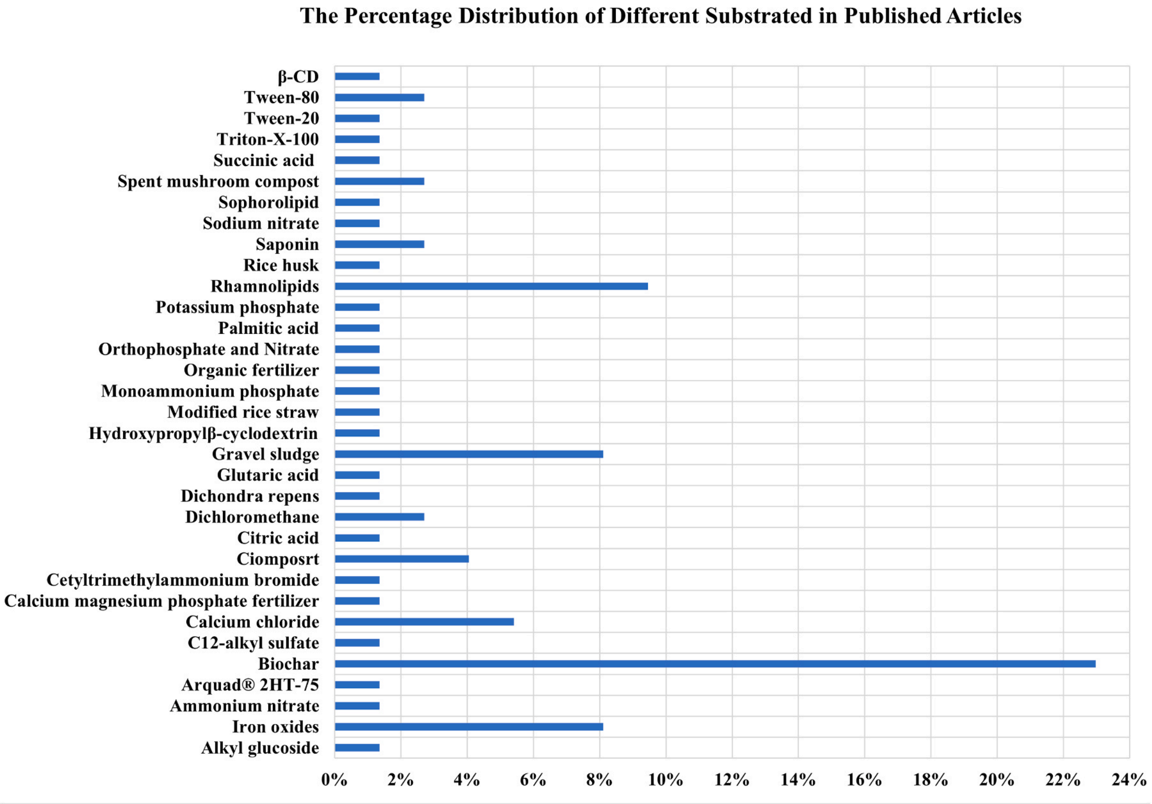

Fig. 9. The percentage distribution of different substrates in published articles.

contaminated sites.

3.2.4. *Cost analysis of soil remediation: synergizing literature review findings with proprietary LCA investigations*

In the pursuit of sustainable remediation strategies, the economic aspect plays a pivotal role. Section 3.2.4 presents a thorough economic evaluation within the realm of soil remediation, blending insights from a comprehensive literature review with our proprietary analytical research. Initially, we meticulously examined published articles to understand the spectrum of costs associated with various remediation strategies, as reported by previous researchers. This literature review serves as a foundation, offering a baseline of financial data and highlighting cost trends and considerations in the field of soil remediation.

Building upon this groundwork, we further expanded our investigation through an extensive Life Cycle Assessment (LCA) analysis. Our LCA study was conducted to provide a more in-depth and nuanced understanding of the costs, extending beyond the scope of the literature review. By applying LCA to several remediation approaches, we aim to fill in the gaps left by prior studies and offer a more comprehensive perspective on the economic implications of soil remediation.

The integration of literature-derived data with our LCA results equips decision-makers with a robust and multifaceted understanding of remediation costs. This unique combination of retrospective analysis and forward-looking assessment forms a valuable resource for stakeholders in the remediation sector, enabling them to make more informed, economically sound decisions that align with environmental sustainability objectives.

In this section, we present a radar chart analysis that interprets soil remediation methods through the lenses of efficiency and cost-effectiveness, contextualized by their representation in academic research (Fig. 10) [78,223]. The chart reveals a significant bias in scholarly literature towards biological treatments, with 84.72% of published articles endorsing them for their cost-effectiveness. However, despite their popularity, biological methods have limitations, such as extended degradation periods and reduced efficacy in removing heavy PAHs, scholars suggest these methods are more suited to non-urgent cases due to their slower degradation rates and challenges in sustaining active microbial communities [3,78,223]. Contrastingly, physical treatments account for only 5.08% of the research, as indicated by the radar chart. This scarcity is likely a result of their lower efficiency, coupled with the complexity and higher costs of implementation. These limitations have driven academic investigations towards optimizing physical methods or integrating them with other treatments for better results [224–226]. Chemical treatments, while deemed most effective by the radar chart, represent just 10.2% of the studies This smaller percentage reflects concerns over high operational costs and potential toxic by-product formation [61,227,228]. The challenge for chemical treatment advocates lies in mitigating these drawbacks without sacrificing remedial efficiency.

In summary, the radar chart offers a comprehensive analysis, illustrating the crucial trade-offs among different soil remediation methods. It underscores the need to balance immediate and long-term benefits, as well as discrepancies between lab and field efficiencies. While chemical remediation shows long-term advantages, its academic representation is limited due to concerns over costs and by-products. Physical remediation, though less prevalent in research, offers a balanced profile of benefits. Biological remediation, the most researched due to its short-term cost-effectiveness and lab efficiencies, faces challenges with slow degradation times and field application. This analysis is invaluable for stakeholders in environmental management and remediation, highlighting the necessity of tailoring remediation strategies to specific objectives and constraints, such as cost, efficiency, time, or environmental impact. It equips decision-makers with a deeper understanding of each method's role in a comprehensive soil remediation strategy, enabling informed and strategic choices that reflect both current research and practical ground realities.

To enhance our understanding of the financial implications of various soil remediation methods, we carried out an extensive

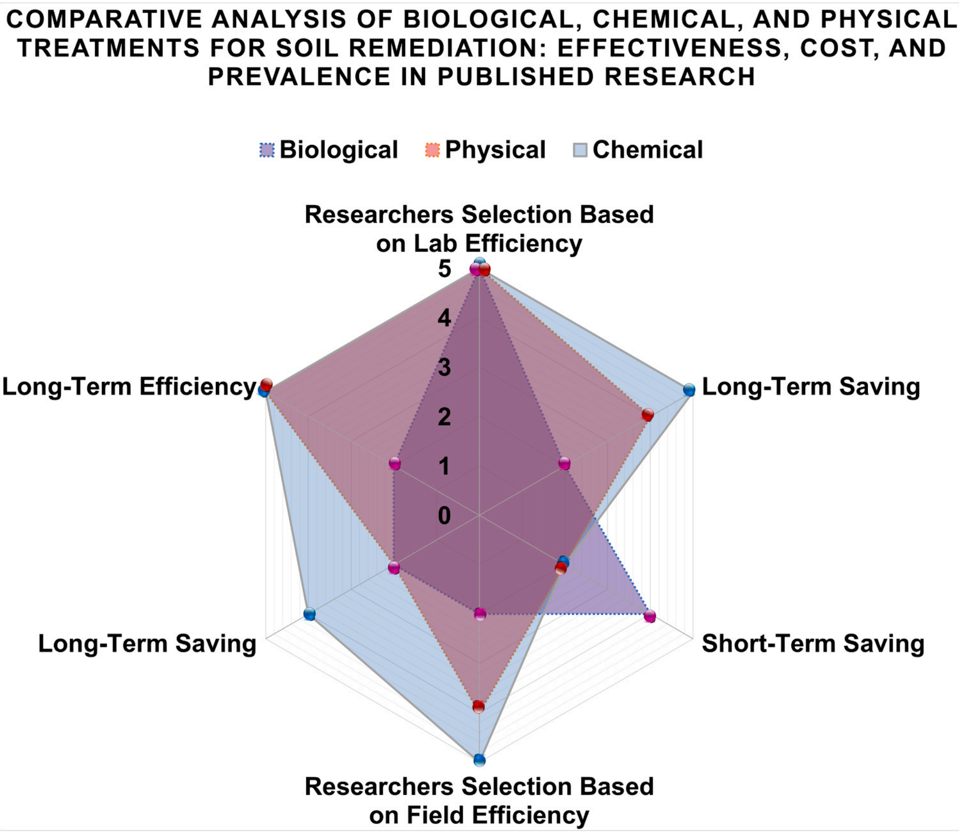

Fig. 10. Comparative Analysis of Biological, Chemical, and Physical Treatments for Soil Remediation: Effectiveness, Cost, and Prevalence in Published Research: presents a comparative analysis of three different soil remediation approaches: biological, chemical, and physical. Each axis on the radar graph represents a different criterion for evaluating three remediation methods; biological remediation (Purple), physical remediation (red), and chemical remediation (Light Blue) based on six metric criteria: Researchers Selection Based on Lab Efficiency, Researchers Selection Based on field Efficiency, Short-Term savings, and long-Term Saving.

comparison of thirteen different remediation techniques, including physical, biological, and chemical methods. These techniques are specifically used for addressing soil contamination caused by petroleum hydrocarbons and heavy metals. The life cycle assessment (LCA) methodology was employed for this analysis. The primary goal was to identify key environmental hotspots in these remediation processes and to evaluate nine different life cycle impact assessment criteria, particularly focusing on the costs associated with each remediation technique. This cost analysis is crucial for comprehending the financial aspects of the environmental impacts of these methods.

This study’s scenario for remediation data analysis revolves around qualitative and quantitative assessments using LCA. LCA is a widely recognized method for evaluating the environmental and economic performance of traditional remediation systems. It involves quantifying potential environmental burdens associated with a product, process, or activity, including the identification and measurement of energy and material usage, as well as environmental emissions. LCA is a robust tool for identifying and evaluating opportunities for environmental enhancement (Martins et al., 2017). Therefore, LCA is aptly suited for examining the effects of various remediation processes. LCA is classified as either consequential or attributional, especially in the context of soil remediation. Attributional LCA evaluates the inherent residual contamination or secondary effects throughout the life cycle of the method. In contrast, consequential LCA focuses on secondary impacts and considers the environmental and economic consequences resulting from the remediation process [229]. LCA has been extensively applied to study the potential effects of soil contamination treatments for heavy metals and PAHs, highlighting its value as a management tool for assessing the environmental consequences of various soil remediation methods targeting different contaminants [230,231]. Despite the extensive application of LCA, no comprehensive studies have been conducted to analyze the remediation of soil contaminated with petroleum hydrocarbons and heavy metals comprehensively and compare across thirteen distinct remediation approaches. Therefore, the primary objective of this study is to assess the environmental impact of physical, biological, and chemical techniques for remediating soil contaminated with these substances, using LCA as the framework.

In our LCA, we included thirteen distinct remediation approaches such as Excavation + off-site treatment, Soil Vapor Extraction (SVE), Chemical Oxidation (S-ISCO), Thermal Desorption (ISTD), Sheet Pile Wall, Pumping, Dual Phase Extraction (DPE), Stimulation Reductive Dechlorination process (SRD), Soil Mixing with micro-Scale ZVI, Natural Attenuation (NA), Passive Soil Vapor Extraction (PSVE), Steam Enhanced Extraction, and Thermal Resistivity (ERH). These methods were evaluated against key decision criteria like resource requirements, economic impact, environmental impact, technical requirements, robustness, and remediation efficiency. These criteria are essential in addressing the sustainability of the remediation approaches as required by stakeholders. In our LCA, each remediation technology’s environmental impact was qualitatively assessed on a scale from 1 to 5, where 1 indicates the maximum negative effect and 5 indicates the maximum positive effect. The weights assigned to each criterion were aggregated to determine the final score for each remediation approach. We have developed a sophisticated Excel-based calculation tool designed to support decision-making in the early stages of soil remediation projects. This tool is invaluable for assessing soil pollution at specific sites, providing a comprehensive framework for planning. It stands out for its ability to facilitate optimization by enabling comparisons of various remediation alternatives at different levels, including strategic, engineering, and specific operational aspects. When choosing a remediation strategy, this tool helps weigh crucial factors such as the effectiveness of the remediation method in achieving the set goals, alongside considerations of cost and time. By integrating these elements, the tool assists in making informed, efficient decisions tailored to the unique requirements of each remediation project. In conclusion, the increasing focus on sustainability in construction projects highlights the importance of carefully considering resource consumption and environmental impacts at both local and broader scales in remediation activities. Our research is centered on the thorough integration of key decision parameters to assess ecosystem sustainability. These parameters are crucial in refining and improving various remediation strategies, enabling more advanced planning, in-depth scenario analysis, and providing valuable policy recommendations for decision-makers.

Our results indicate that the choice of remediation method is largely influenced by specific contamination circumstances, adherence to regulatory standards, and cost-benefit considerations. Each approach has its own advantages and disadvantages, requiring a decision-making process informed by a deep understanding of these factors (Table S2) (Fig. S2). Excavation + Off-Site Treatment is notable for its relatively high LCA score of 19, reflecting its efficiency in resource use. However, it generates significant waste, primarily from the transport and processing of excavated materials. While its emissions and toxicity levels are moderate, suggesting a moderate environmental impact, its energy consumption and carbon footprint are relatively low, indicating moderate operational energy demand. The initial cost is moderate with no significant operational or dismantling expenses, making it appealing for short-term projects. But, the high waste output may lead to additional long-term environmental management costs. Soil Vapor Extraction (SVE) achieves a balanced LCA score of 20, reflecting a compromise between resource use and environmental impact. It excels in minimizing emissions, reducing air quality impact, but has higher toxicity and waste production, likely due to chemicals used in extraction. SVE has the lowest energy consumption among more active methods, and a low carbon footprint, underscoring its sustainability. However, these ecological benefits come with high planning, construction, and operational costs, making it a costly long-term investment. Chemical Oxidation - S-ISCO with LCA score of 17, has initial high resource-intensive, mainly due to the chemicals used in treatment. It has moderate emissions but high toxicity and waste production. The method is energy-hungry, reflected in high energy consumption and carbon footprint, attributed to chemical production and application. Financially, it requires significant investment in planning and construction, indicative of the complexity of chemical treatments in remediation. Thermal Desorption - ISTD, scoring 43 on the LCA scale, is the most resource-demanding among conventional methods. It has high emissions, toxicity, and waste generation, likely from combustion or heating in soil treatment. This method is extremely energy-intensive, with the highest energy consumption and carbon footprint, due to high temperatures required to volatilize contaminants. Financially, it is very costly, suitable primarily for cases where less aggressive methods are ineffective. Sheet Pile Wall distinguishes itself with a lower LCA score of 10, indicating its role as a more passive and resource-efficient containment strategy. Its notably low emissions, toxicity, and waste production suggest minimal environmental disruption, likely due to its focus on containment rather than active treatment. The energy requirements and carbon footprint are low, enhancing its environmental benefits. Financially, with moderate construction costs and potentially negligible operation and dismantling costs, it stands as an economically viable option. Pumping - P, though sharing with LCA score of 22 but contribute significantly in environmental impact. It shows high emissions and toxicity, along with moderate waste production, likely due to the continuous operation of pumping machinery and treatment of extracted contaminants. The high energy demands and carbon footprint reflect the ongoing nature of the operations. The initial costs are relatively low, but higher operational expenses suggest a substantial long-term financial burden.

Dual Phase Extraction - DPE, with a moderate LCA score of 20, strikes a balance between resource efficiency and environmental impact. It has lower emissions but higher toxicity, likely due to the simultaneous extraction of liquid and vapor contaminants. The energy requirements and carbon footprint are moderate. Financially, DPE requires moderate investment for planning and construction, with additional operational and dismantling costs over time. Stimulation Reductive Dechlorination process - SRD scores an exceptionally low LCA score of 15, indicating high efficiency and minimal resource use. It shows minimal environmental footprint across emissions, toxicity, and waste. Moderate energy consumption and a low carbon footprint enhance its sustainability. However, the initial costs are relatively high, and the dataset lacks information on operational and dismantling costs. Soil Mixing with micro-Scale ZVI scores a low LCA of 18, reflecting effective resource conservation. It shows moderate emissions, higher toxicity, and moderate waste, possibly due to in-situ treatment with reactive agents. High energy consumption and carbon footprint, likely due to mechanical mixing and material use, are offset by considerable upfront costs and more manageable ongoing expenses. Natural Attenuation - NA, with an LCA score of 12, the second lowest among all methods, exemplifies sustainability. It minimizes impact across all environmental criteria, relying on natural degradation processes. Negligible energy consumption and costs are notable, though operational costs may accrue for long-term monitoring. Passive Soil Vapor Extraction - PSVE, with an LCA score of 17, shows low emissions and waste but moderate toxicity, likely due to passive venting. It requires moderate energy and incurs a reasonable carbon footprint. Financially, it demands significant initial and operational investments. Steam Enhanced Extraction scores 34 on the LCA scale, reflecting a more balanced environmental impact. High emissions, toxicity, and waste stem from the steam generation and extraction processes. The method is energy-intensive, with high costs highlighting specialized equipment and energy needs. Thermal Resistivity - ERH, with an LCA score of 39, is high-intensity, producing high emissions, very high toxicity, and significant waste, primarily from large-scale soil heating. Its very high energy consumption and carbon footprint, along with considerable financial outlay, reflect the specialized equipment and operational energy costs.

In evaluating these methods, it is crucial to balance environmental performance, cost considerations, and site-specific demands. Lower-impact, cost-effective methods like Natural Attenuation may be preferable for less contaminated sites, while more intensive methods might be necessary for heavily contaminated areas. Each approach should be thoroughly evaluated based on site-specific conditions, regulatory compliance, and long-term sustainability goals. In summary, our study emphasizes the need to tailor the selection of a remediation approach to the unique contamination circumstances, regulatory adherence, and thorough cost-benefit analysis. Each method presents specific trade-offs, requiring a decision-making process informed by a deep understanding of these critical factors.

3.3. Parts 3 How do various factors influence the effectiveness of biological, chemical, and physical remediation methods, both individually and combined, in co-contaminated soils, and what role do specific agents play in the degradation, immobilization, or removal of heavy metals and PAHs under diverse environmental conditions?

The combined treatment techniques, which involve the use of multiple remediation approaches, have shown potential in overcoming some of the drawbacks associated with single treatment techniques in the remediation of co-contaminated soils. By integrating different methods, combined treatments can target a wider range of contaminants and enhance the overall efficiency of the remediation process. However, there are still several challenges and drawbacks that need to be addressed in the discussed remediation approaches among published articles. One common concern is related to obtaining consistent results when treatments are applied in mixed environments, such as field

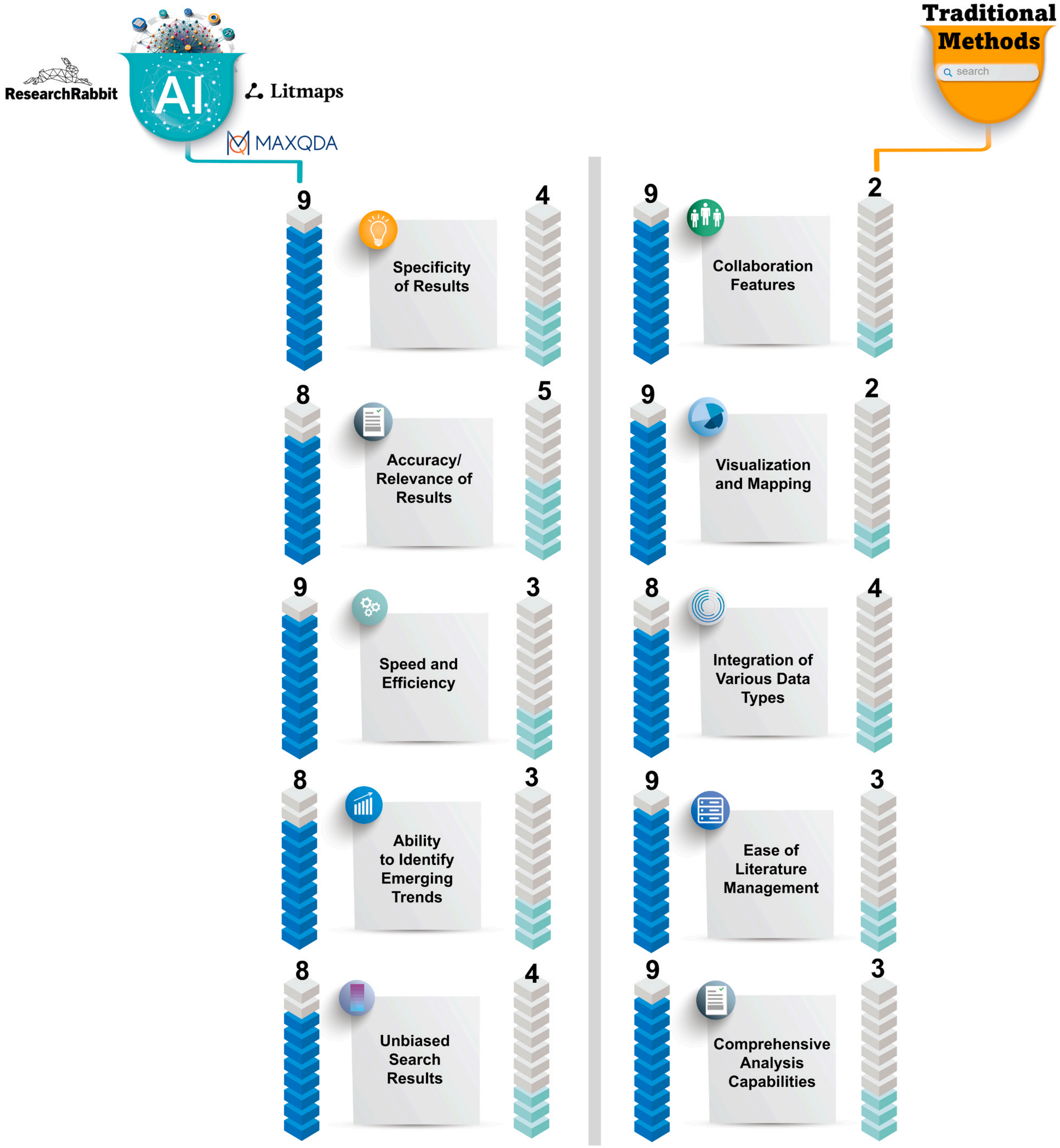

Fig. 11. Comparison Between AI-Search Tools and Traditional Search Tools.

studies, over prolonged periods of time [34,166,200,201]. Many studies have been conducted for relatively short periods, which may not be sufficient to fully explore the potential behavior of biostimulation approaches in removing heavy metals and PAHs from contaminated soil or may lead to contradictory results among published papers. For instance, lab experiments might show that plants inoculated with microorganisms are sufficient to remove certain types of heavy metals (e.g., Cr) and PAHs (e.g., naphthalene) within a very short time (e.g., 2 days). However, the same results may not be achieved when the treatment is subjected to longer timescales [166]. Therefore, longer treatment periods are necessary to accurately assess the true potential behavior of these biological treatments in co-contaminated soils. Another limitation is that many successful outcomes in these studies were based on testing a single type of heavy metal or PAHs compound, which does not reflect the complexity of real environments. This could lead to failure when these treatments are conducted in field studies [166]. To draw accurate conclusions about the efficacy of biological treatments in remediating co-contaminants in soil, it is essential to test therapies for longer time periods under the influence of different contaminants. Moreover, certain microbial and plant species demonstrate different behaviors in removing specific types of heavy metals and PAHs compounds, even with the addition of stabilizing chemicals [166,178–180,199]. This indicates that plant tolerance to heavy metals and PAHs is highly dependent on the specific plant species and microorganisms present in the soil [175]. Consequently, it is crucial to carefully select suitable plant-microbe combinations that are well-adapted to the specific contaminants and soil conditions. Additionally, the success of bioaugmentation and biostimulation techniques has been observed to depend on soil conditions and the types of microorganisms used. Researchers have suggested focusing on discovering natural attenuators that have similar capabilities but are more selective to the specific environmental conditions, to improve the effectiveness of these treatments [201]. In summary, while combined treatment techniques offer promise in addressing some of the challenges associated with single treatment approaches, there are still important limitations that need to be considered and addressed to ensure successful and efficient remediation of co-contaminated soils. Longer treatment periods, consideration of multiple contaminants, and careful selection of appropriate plant-microbe combinations are among the factors that should be given due attention in future remediation studies.

Seasonal variation significantly impacts the efficiency of treatments in degrading PAHs and removing heavy metals from contaminated soil. During winter seasons, the mobility and availability of PAHs fractions and heavy metals may be limited, hindering their removal by different remediation techniques. Moreover, the low temperatures can suppress the effectiveness of soil amendments, impede the activity of microorganisms, and disrupt the uptake of heavy metals and PAHs compounds by plants in the contaminated soil [170]. In studies conducted by Mmom & Deekor, challenges were encountered in removing various heavy metals and PAHs using the landfarming approach due to the complexity of soil's physical and chemical properties and site temperature [200]. The presence of oil in the soil can alter the properties of oil-contaminated sand, negatively affecting the success of combined treatments such as bioventing-biosparging-phytoextraction techniques in clearing heavy metals and PAHs from contaminated soils [34]. These drawbacks in the remediation approaches could possibly be attributed to the accumulation of contaminants near the root area, as well as the strong cation-π interactions between heavy metals and PAHs components, which inhibit the adsorption ability of plants [168].

Heavy PAHs, known for their low water solubility and high sorption capacity, can inhibit microbial activity and negatively impact the efficiency of phytoremediation-compost-amended treatments [172]. For example, the use of biochar may not always lead to sufficient degradation of benzo[*a*]pyrene due to the presence of heavy metals like Cu and improper selection of plant species [168]. Similarly, an increase in the concentration of heavy metals such as Cd can lead to the failure of biochar-biostimulation (*Escherichia sp.*) or biosurfactant-enhanced soil washing methods to remediate Cd and pyrene in co-contaminated soils [171,232]. Therefore, further studies that explore combinations of different plant-microbe-amendment treatments are needed to achieve sufficient removal of PAHs and heavy metals in highly contaminated soils (Huang, H., 2016). Similar observations were made with combined physical-chemical treatments, such as the use of chemicals and electrostatic potential in electrokinetic remediation [173,202]. Thus, before applying any treatment approach, factors like absorption, chemical composition, and spillage quantity in oil-contaminated soils must be thoroughly investigated. The effectiveness of surfactant-washing systems is highly dependent on flow conditions, hydraulic gradient, washing cycles, and the composition of the washing solution [59,60]. Although optimization experiments have been conducted for surfactant-flushing systems, there remains a tendency for the system to favor the removal of one contaminant over the other. Hence, further development of the system is suggested to achieve desirable outcomes in co-contaminated soils containing heavy metals and PAHs [59,60]. Indeed, the concentration and components within combined chemical approaches can influence the removal efficiency of specific contaminants over others. For example, the combination of EDTA-polyethylene glycol dodecyl ether-Tween® 80 was found to effectively remove Pb (100%), but the presence of phenanthrene in the soil dramatically decreased the removal efficiency of Pb (48%) and only a small portion of phenanthrene was degraded (55%) [58]. Similar results were observed in a combined treatment of chemical-phytoremediation, where the accumulation of Cd hindered the degradation rate of benzo[*a*]pyrene in co-contaminated soils [174]. Furthermore, some researchers attempted a combination of three treatment processes using ultrasound-assisted soil washing and bioaugmentation, but significant removal of heavy metals was observed, while PAHs remained largely unaffected in co-contaminated soils [182]. These findings indicate that the effectiveness of combined treatments may vary depending on the specific contaminants present and their interactions within the soil matrix, highlighting the need for careful consideration of treatment combinations for efficient remediation of co-contaminated sites.

In conclusion, our review of combined treatment techniques in the remediation of co-contaminated soils shows promise but also reveals several challenges that require focused attention. While combining methods amplifies the range and efficacy of treatments, inconsistencies arise when applied to complex, real-world conditions. These include variations in seasonal temperature affecting microbial and plant activity, and the complexity of soil properties hindering remediation efforts. One major concern is the lack of long-term studies that reflect the actual behavior of treatments in natural environments. Short-term lab results often do not translate to long-term field effectiveness, creating a gap in our understanding of how well these treatments work over extended periods. The specificity of microbe-plant combinations to particular contaminants and soil conditions necessitates a more tailored approach. In addition, the presence of heavy PAHs and specific heavy metals like Cu and Cd can sometimes compromise the effectiveness of otherwise promising treatments, such as biochar-biostimulation. Other complicating factors include the varying efficiencies of different treatment components in combined chemical approaches, and the need for system optimization in methods like surfactant-washing systems. The presence of multiple contaminants can skew the treatment's efficacy towards one contaminant over another, demanding more integrated and adaptable strategies. Overall, while combined treatments offer a robust framework for addressing co-contaminated soils, the road to optimized, effective, and universally applicable solutions is fraught with challenges. Future research should focus on long-term field studies, tailored microbe-plant combinations, and adaptable treatment strategies that consider the complex interplay of multiple contaminants and environmental factors. This will pave the way for more reliable and efficient remediation techniques capable of addressing the intricacies of co-contaminated soils.

4. Revolutionizing research: a comparative analysis of AI search tools and traditional methods in scientific literature exploration

AI search tools, exemplified by Litmaps and ResearchRabbit, represent a significant advancement in scientific article research. These tools are designed to enhance search relevance through adaptive learning, aligning closely with user interests and research topics. They excel in filtering out irrelevant papers, thereby sharpening the focus and specificity of search results. Moreover, they stand out for their accuracy, providing unbiased results and not showing preferential treatment

Table 4
Evaluating the Efficacy of AI Search Tools vs. Traditional Methods in Scientific Research: A Criteria-Based Comparative Scorecard.

Criteria	AI Search Tools	Traditional Search Methods
Specificity of Results	9	4
Accuracy/Relevance of Results	8	5
Speed and Efficiency	9	3
Ability to Identify Emerging Trends	8	3
Unbiased Search Results	8	4
Collaboration Features	9	2
Visualization and Mapping	9	2
Integration of Various Data Types	8	4
Ease of Literature Management	9	3
Comprehensive Analysis Capabilities	9	3

towards certain publishers or authors. This is pivotal in bridging knowledge gaps by bringing lesser known but pertinent papers to the forefront. In terms of improving the search process, AI search tools like these utilize visual mapping to elucidate the connections between different studies, aiding in the comprehension of complex research landscapes. They are adept at identifying new and emerging research areas, significantly streamlining the journey from initial search to dataset creation. The incorporation of tools for advanced discovery and interactive visualizations enhances the research experience further. These platforms also foster collaborative efforts, enabling team members to share and discuss their findings within a unified system.

Another category of AI search tools, such as MAXQDA, focuses on qualitative and mixed methods data analysis. These tools offer efficient file management and facilitate communication within teams, thus simplifying literature review processes, especially for meta-analyses. They excel in organizing and importing materials, with features like automatic coding of imported literature for streamlined retrieval and analysis. Documentation tools within these platforms help in meticulously tracking search strategies and insights. AI assistance in literature reviews is another notable feature, with AI-generated summaries and subcodes simplifying data analysis. They also provide quick access to definitions, enhancing the review process. The coding and retrieval of key segments are made more nuanced through a range of coding tools, such as in-vivo coding and emoticodes. Additionally, the Text Search & Autocode feature allows researchers to explore large volumes of text without needing to read everything in detail. The integration of qualitative and quantitative data is also seamlessly handled by these tools, offering functionalities like joint displays and crosstabs for a more comprehensive analysis. They assist in paraphrasing and summarization, providing a condensed view of extensive literature. The data visualization capabilities, including tools like Word Clouds and frequency analysis, aid in identifying patterns and can be exported to enrich research reports. Furthermore, these tools allow for the creation and comparison of document groups based on various criteria and provide quantitative tools for theme evaluation (Fig. 11).

In contrast, traditional search methods rely heavily on the effective selection of keywords by users, often resulting in lower specificity and a mix of relevant and irrelevant results. They lack the adaptive learning components of AI tools and require significant manual effort for literature mapping. Traditional methods may also exhibit biases towards well-known journals, authors, and institutions, with articles scattered across different databases due to financial or access constraints. These methods are generally more time-consuming and labor-intensive, lacking the tools for rapid and comprehensive literature mapping and analysis. They also present a higher risk of missing out on relevant but less prominent research, with limited capabilities in identifying emerging trends and gaps in existing research (Fig. 11).

Employing a comprehensive scorecard methodology with a grading scale ranging from 1 to 10, we conducted a thorough comparative evaluation of AI Search Tools versus Traditional Methods specifically within the domain of scientific research. This approach involved assessing various dimensions and criteria critical to research effectiveness and efficiency. Parameters such as speed of information retrieval, accuracy of search results, user-friendliness, integration with existing databases, cost-effectiveness, and the ability to uncover hidden patterns or connections were meticulously examined. Each parameter was assigned a score based on its performance, offering an insightful quantitative assessment. This allowed for a nuanced analysis, highlighting the strengths and potential limitations of both AI-powered search tools and traditional research methodologies, thereby providing a robust framework for evaluating their respective impacts on the scientific research landscape. AI Search Tools consistently outperformed Traditional Methods across multiple dimensions, including specificity of results, accuracy and relevance of findings, speed and efficiency in research, and the capability to identify emerging trends. Moreover, AI tools demonstrated a higher level of impartiality in search results, superior collaboration features, and more advanced options for visualization and mapping. They also excelled in the integration of diverse data types, ease of managing literature, and providing comprehensive analysis capabilities. These findings highlight the significant advancements AI-based tools bring to the realm of scientific research, offering enhanced efficiency, deeper insights, and a more collaborative environment compared to traditional research methods (Table 4):

- **Specificity of Results (AI: 9, Traditional: 4):** AI search tools leverage sophisticated algorithms to learn and adapt to the user's research interests. They can refine searches more effectively, leading to highly specific results. Traditional methods, reliant on manually input keywords, often retrieve a broader range of results, many of which may be irrelevant, thus scoring lower on specificity. In terms of
- **Accuracy/Relevance of Results (AI: 8, Traditional: 5):** AI systems excel in filtering and presenting the most relevant and accurate papers, thanks to their advanced data processing capabilities. Traditional search methods, while effective, may struggle with the precision of results, especially in fields with a vast body of literature.
- **Speed and Efficiency (AI: 9, Traditional: 3):** The speed at which AI tools can process, analyze, and retrieve information is significantly higher than traditional methods. AI tools automate and streamline many aspects of the research process, resulting in time-saving and efficiency. Traditional methods, being more manual and linear, are inherently slower and less efficient.
- **Ability to Identify Emerging Trends (AI: 8, Traditional: 3):** AI tools are adept at detecting patterns and emerging trends within large datasets, a task that is challenging and time-consuming with traditional methods. This ability is crucial for staying ahead in rapidly evolving research fields.
- **Unbiased Search Results (AI: 8, Traditional: 4):** AI tools aim to minimize biases by providing a wide range of sources. However, they are not completely free from biases inherent in their programming and data sources. Traditional searches, especially when limited to specific databases or journals, might reflect biases towards more prominent authors or institutions.
- **Collaboration Features (AI: 9, Traditional: 2):** Modern AI tools often include features that support collaboration, such as sharing capabilities and joint data analysis. Traditional methods, in contrast, are more isolated, requiring additional effort for collaborative research.
- **Visualization and Mapping (AI: 9, Traditional: 2):** The ability of AI tools to visually map relationships between research papers greatly enhances understanding and discovery. Traditional methods lack such sophisticated visualization tools, making it difficult to discern connections in large volumes of data.
- **Integration of Various Data Types (AI: 8, Traditional: 4):** AI tools can handle and integrate diverse data types, including qualitative and quantitative data, more effectively than traditional methods, which might require separate tools for different data types.
- **Ease of Literature Management (AI: 9, Traditional: 3):** AI tools streamline the organization, storage, and retrieval of literature. In contrast, traditional methods often involve manual organization, which is more time-consuming and less efficient.
- **Comprehensive Analysis Capabilities (AI: 9, Traditional: 3):** AI tools provide a range of analytic features, offering comprehensive insights that traditional methods cannot match, especially when dealing with large datasets or complex research questions.

The comparison highlights the superiority of AI search tools over traditional methods in various aspects of scientific research. AI tools demonstrate remarkable strengths in specificity, accuracy, efficiency, and analytical capabilities. They offer advanced features like trend identification, unbiased search results, collaborative functionalities, sophisticated data visualizations, and comprehensive data integration and management. However, it's important to acknowledge that AI tools are not without limitations. The potential for inherent biases in AI algorithms and the quality of data sources can impact the neutrality of search results. Moreover, the accessibility and user-friendliness of some AI tools may be a barrier for certain researchers.

The way forward involves a hybrid approach that leverages the strengths of both AI and traditional methods. Researchers should be encouraged to use AI tools for their efficiency and advanced capabilities while remaining critical of their limitations. Continuous improvement and transparency in AI algorithms will enhance their reliability. Additionally, training and support for researchers in using these tools can maximize their benefits.

In conclusion, AI search tools offer a dynamic, efficient, and comprehensive approach to literature search and analysis compared to traditional methods. They excel in specificity, accuracy, and uncovering hidden connections and emerging trends. While traditional methods still hold value, they are more time-consuming and heavily reliant on the researcher's input and expertise. AI tools, with their advanced features for collaboration and data integration, are proving to be invaluable assets in modern research methodologies.

5. Conclusion

In this comprehensive review, we meticulously analyzed a vast array of literature on soil remediation, focusing on sites co-contaminated with heavy metals and PAHs. Our methodology harnessed the prowess of AI tools such as ResearchRabbit, Litmaps, and MAXQDA, enhancing the precision and scope of our analysis. ResearchRabbit facilitated the efficient aggregation of pertinent research, ensuring a holistic representation of the field's current trajectory. Litmaps provided advanced visualization tools, uncovering trends and correlations within the data, while MAXQDA offered a robust platform for qualitative analysis, enabling a nuanced understanding of the thematic undercurrents in the literature.

Our exploration delved into the intricate interplay of cation-π interactions and soil properties, revealing how these factors intricately influence the solubility and remediation dynamics of heavy metals and PAHs. The study illuminated the nonlinear adsorption patterns of heavy metals, shaped by soil characteristics such as clay type and organic content. The investigation recognized the emerging preference for combined remediation strategies, with biostimulation-bioaugmentation being particularly notable for its laboratory efficacy, albeit posing challenges in field applications due to higher costs and environmental variability. Significantly, the research highlighted the pivotal role of plant-microbe symbiosis in phytoremediation, underscoring the effectiveness of species like Medicago sativa L. and Solanum nigrum L. in concert with beneficial microbes. The study acknowledged the enhancement of treatment efficiency through the strategic incorporation of biochar, surfactants, and chelating agents such as EDTA, emphasizing the necessity for site-specific remediation strategies to accommodate diverse environmental conditions. A critical component of our analysis involved the Life Cycle Assessment (LCA), which provided valuable insights into the environmental and financial implications of various remediation methods. The assessment compared the effectiveness and costs of thirteen distinct remediation techniques, including physical, biological, and chemical methods, against the backdrop of site-specific requirements and regulatory frameworks. The findings advocate for a tailored approach to remediation, balancing environmental sustainability, cost-effectiveness, and the unique demands of each contaminated site.

In conclusion, our study underscores the imperative for an integrative, adaptive approach to soil remediation. It advocates for a harmonious blend of various methods, meticulously aligned with the distinct challenges of each contaminated site, regulatory compliance, and long-term decontamination goals. This nuanced strategy, informed by indepth research and innovative methodologies, is instrumental in advancing our collective ability to effectively address and restore contaminated soil environments. The insights garnered from this review not only serve as a cornerstone for researchers, policymakers, and practitioners in the field of environmental remediation but also pave the way for future investigations, aiming to surmount the limitations and hurdles associated with the remediation of co-contaminated soils.

6. Emerging trends and future perspectives

The comprehensive analysis of published articles on the remediation of co-contaminated soils with heavy metals and PAHs has provided valuable insights into the current state of research in the field. However, there are several areas where further research is needed to address existing gaps and challenges. The future results section outlines potential research directions and expected outcomes that could contribute to advancing the field of co-contaminated soil remediation.

1. Long-term Field Studies: One of the key limitations observed in the reviewed literature was the lack of long-term field studies. To better understand the effectiveness and sustainability of remediation approaches, future research should focus on conducting comprehensive field trials with prolonged treatment periods. Long-term studies will provide more accurate assessments of treatment efficiency, especially in real-world environments with varying seasonal conditions and weather patterns.
2. Combination of Multiple Treatment Approaches: The integration of multiple treatment methodologies has shown promising results in some studies. However, more research is needed to explore the synergistic effects of combining different treatments, such as biological-biological, biological-physical, and chemical-physical approaches. Future studies should investigate the potential benefits of using complementary treatment techniques to enhance the removal of both heavy metals and PAHs in co-contaminated soils.
3. Plant-Microbe Interactions: Understanding the complex interactions between plants and microbes in co-contaminated soils is essential for improving the efficiency of phytoremediation and bioaugmentation techniques. Future research should focus on characterizing the specific microbial species and their functions in degrading PAHs and immobilizing heavy metals. Identifying plant-microbe synergies will help optimize remediation strategies and select the most suitable plant-microbe combinations for specific contaminated sites.
4. Innovative Substrates and Amendments: The use of biochar and other amendments has shown promise in enhancing treatment efficiency. Future research should explore novel substrate materials and organic amendments that can further improve the performance of remediation techniques. Additionally, investigating the interactions between different amendments and contaminants will aid in designing tailored approaches for specific co-contaminated soil scenarios.
5. Field-Scale Implementations: While many studies have been conducted in laboratory or controlled settings, there is a need for more research focusing on large-scale field implementations. Field-scale studies can provide valuable insights into the practical challenges and limitations of implementing remediation strategies in real-world contaminated sites. Moreover, such studies will help validate the effectiveness and economic feasibility of the proposed approaches.
6. Integrated Risk Assessment: Future research should also consider conducting integrated risk assessments to evaluate the potential risks and benefits of remediation strategies. This involves assessing not only the removal efficiency of contaminants but also potential ecological and human health impacts. By incorporating risk assessments, policymakers and stakeholders can make more informed decisions regarding the selection of appropriate remediation approaches.

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Salvatore Calabrese: Writing – review & editing. **Salah Al-Enezi:** Writing – review & editing. **Patricia K. Smith:** Writing – review & editing, Conceptualization. **Rabi Mohtar:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Data curation, Conceptualization. **Zainab Ashkanani:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Meshal Abdullah:** Writing – original draft. **Xingmao Ma:** Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2024.133813.

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