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Recent developments and prospects of sustainable remediation treatments for major contaminants in soil: A review

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Abstract: Rapid industrialisation and urbanisation are contributing to the entry of emerging contaminants into the environment, posing a significant threat to soil health and quality. Therefore, several remediation technologies have been investigated and tested at a field scale to address the issue. However, these remediation technologies face challenges related to cost-effectiveness, environmental concerns, secondary pollution due to the generation of by-products, long-term pollution leaching risks, and social acceptance. Overcoming these constraints necessitates the implementation of sustainable remediation methodologies that prioritise approaches with minimal environmental ramifications and the most substantial net social and economic advantages. Hence, this review delves into diverse contaminants that threaten soil health and quality. Moreover, it outlines the research imperatives for advancing innovative remediation techniques and effective management strategies to tackle this concern. The review discusses a remediation treatment train approach that encourages resource recovery, strengthens the circular economy, and employs a Life Cycle Assessment (LCA) framework to assess the environmental impacts of different remediation strategies. Additionally, the study explores mechanisms to integrate sustainability principles into soil remediation practices. It underscores the necessity for a comprehensive and systematic approach that takes into account the economic, social, and environmental consequences of remediation methodologies in the development of sustainable solutions.

Keywords: Clean-up, Contamination, Life cycle assessment, Resource recovery, Sustainability

1. Introduction

Soil pollution from chemical substances threatens soil quality and functionality (Sun et al., 2019; Munzel et al., 2023). The detection and monitoring of new and emerging contaminants in soil have become critical due to their potential implication on the environment and human health. Emerging contaminants encompass a diverse range of chemical compounds originating from various human activities, including domestic, healthcare, agricultural and industrial processes, reflecting the ubiquitous presence of these substances in our daily lives (Martin-Pozo et al., 2019). Contaminants in the soil matrix adhere either through chemical adsorption or become trapped within the pore spaces surrounding the soil grains, as the soil is a porous and solid complex matrix made of a mixture of mineral particles and organic matter (Trellu et al., 2021). Subsequently, they can enter the food chain, posing a risk to human health due to long-term exposure, even if they are present at very low concentrations (Palansooriya et al., 2020; Shaheen et al., 2020). With over 5 million contaminated sites globally, representing approximately 20 million ha of contaminated land (He et al., 2015), remediation of contaminated soil is considered one of the main challenges that environmental management practitioners are facing (He et al., 2015). In the last five decades, various in-situ and ex-situ remediation techniques have been developed to contain, clean, and restore contaminated soil (Liu et al., 2018). While conventional remediation technologies have proven effective, they have raised environmental and social concerns, such as the potential for secondary pollution, long-term effects and societal acceptance (Wang et al., 2020; Labianca et al., 2023). This development has given rise to the concept of sustainability, emphasising that the environmental, social, and economic aspects of the remediation process, including the impacts of all materials used from primary resource extraction to the final disposal of generated materials or by-products, should be taken into account in the decision-making process. Thus, it is crucial to identify methods and tools that can effectively assess the sustainability of remediation techniques in addressing major and emerging contaminants from household and industrial sources and the entire life cycle of the process (Visentin et al., 2019).

Recently, sustainable remediation technologies such as SuRF-UK, ReCon Soil and CL:AIRE, which are approaches and methods used to clean up contaminated sites while minimising negative impacts on the environment, human health and society, have received significant attention as a strategy to control soil pollution, improve soil health, and maximise ecological sustainability, aiming at recovering valuable resources, minimising human impacts and saving energy (Akhtar et al., 2020; Michael-Igolima et al., 2022). However, as new and emerging compounds are discovered as soil contaminants, identifying and selecting a sustainable technology for remediating contaminated soil remains complex. Therefore, this review paper aims to address the five objectives: i) providing an overview of the sources of contamination in soil; ii) evaluating different remediation methods in terms of their characteristics, advantages and limitations, and application status; iii) looking at techniques and opportunities that can simultaneously treat soil and recover resources to enhance the circular economy; iv) comparing environmental impacts of different soil remediation technologies based on life cycle assessment (LCA), and v) exploring holistic frameworks and tools to help integrating sustainability into soil remediation practices. Overall, it underscores the importance of adopting a holistic approach that considers the economic, social, and environmental impacts of remediation methods in developing sustainable solutions for soil remediation. Thus, this paper demonstrates how sustainability principles are incorporated into contemporary approaches for soil. Additionally, the paper highlights the integration of circular economy principles into soil remediation practices, emphasizing recycling and reuse as a novel aspect.

2. Major sources of soil contamination and sustainable remediation technologies

Soil contamination occurs when substances that are hazardous to soil health are buried, spilled or allowed to migrate in the soil. These hazardous substances could be inorganic (e.g., asbestos and heavy metals) or organic (e.g., agrochemicals and polycyclic) (Figure 1), emanating from natural and anthropogenic sources. Natural sources include volcanic eruptions, forest fires, and weathering of rocks and minerals that contain toxic chemicals.

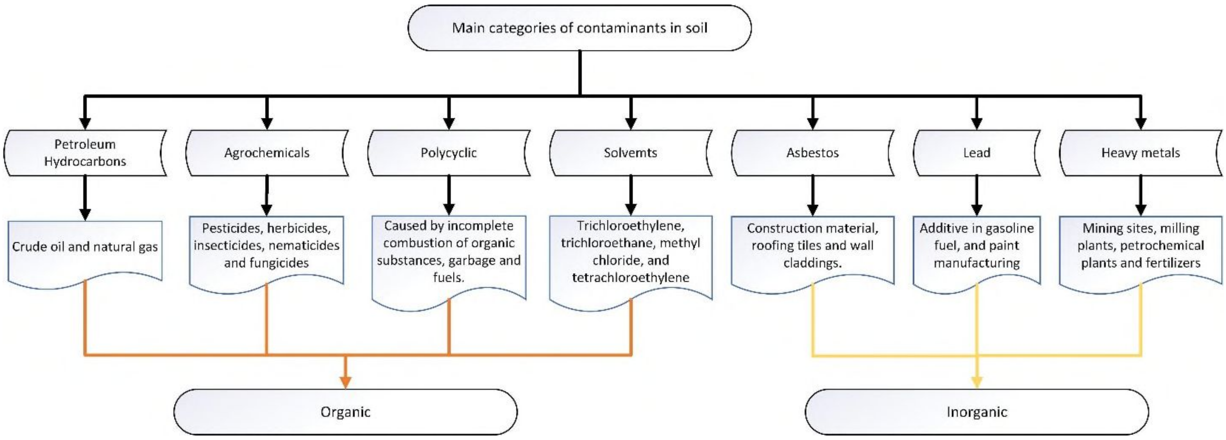

Figure 1. Main types of soil contaminants

Anthropogenic sources, however, are the major contributors to soil contamination. These sources include domestic and household products which include cleaning products, pharmaceuticals and personal care products (PPCPs), paints and solvents and pest control chemicals; industrial activities such as mining, smelting, and manufacturing; agricultural activities such as the use of pesticides, fertilizers, and manure; improper disposal of household and industrial waste; and accidental spills of chemicals and pollutants (Priya et al., 2014). Soil contaminants broadly emanate from organic or inorganic contaminants (Fig. 1). Organic and inorganic soil contaminants pose significant threats to soil quality, ecosystem health, and human well-being. Organic contaminants, primarily composed of carbon-based compounds, encompass a diverse range of substances, including hydrocarbons, pesticides, polychlorinated biphenyls (PCBs), and pharmaceuticals (Taghavi et al., 2022). Whether occurring naturally or as a result of human activities, these inorganic substances can accumulate in soil and cause soil salinity, toxic heavy metal concentrations, altered pH levels, and nutrient imbalances (Sahithya, et al., 2022). Both organic and inorganic contaminants can have far-reaching consequences, impacting soil fertility, plant growth, groundwater quality, and even human health if not adequately managed and mitigated through sustainable soil remediation and pollution prevention strategies (Priya et al., 2014; details in Supplementary data Fig. 1).

Emerging contaminants are a diverse group of substances that have recently gained attention due to their potential to negatively impact ecosystems and human health. These contaminants encompass various classes of chemicals, including pharmaceuticals, personal care products, pesticides, and industrial compounds. Unlike well-studied legacy contaminants, emerging contaminants are often not regulated or adequately monitored, which makes their presence and effects in the environment less understood (Chaturvedi, et al., 2021). One key concern with emerging contaminants is their ability to persist in the environment and accumulate in organisms over time (Table 1, Aggelopoulos, 2022). Many of these substances are not easily degraded through natural processes, and their continuous release into water bodies and soil can lead to bioaccumulation in aquatic and terrestrial food chains. Considering the dynamic nature of emerging contaminants and the long-term impacts on public health and the environment, research needs to assess their environmental fate, toxicity, and potential risks (Barrios-Estrada et al., 2018), ultimately guiding the development of regulatory measures and mitigation strategies to safeguard our environment and health (Akhbarizadeh et al., 2020; Chaturvedi, et al., 2021; Priya et al., 2022).

These synthetic organic chemicals are becoming an increasing challenge in soil contamination because they are resistant to degradation, pervasive, toxic in nature, often highly persistent and with unknown long-term effects (Priya et al. 2022). In addition to their long-term impacts on receptors, they pose a challenge for sustainable remediation as their fate, transport and environmental behaviour are largely unknown. As a result, it is difficult to comprehensively assess their potential risks to support the development of appropriate management strategies (Rathi et al., 2021).

Table 1. Type and source of the main chemicals contaminating the soil

Contaminants	Examples of compounds	Source	Effect in biota	Reference
PAH	Benzo[a]pyrene, Chrysene, Fluoranthene	Petroleum industry, oil refineries, gasoline stations, manufactured gas plants, wood preservation sites, municipal waste incineration, automobile exhaust	Destroys biodiversity and impacts on species abundance	Valentin et al. (2013), Van Elsas et al. (2012), Zhang et al. (2021).
Heavy metals	As, Cu, Zn, Cd, Pb, Hg, Cr, Ni	Military facilities, old mines, hydrocarbon refineries, agriculture, gasoline stations, sawmills and wood preservation sites, metallurgical and mining industry	High concentration declines microbial activity and impact on agriculture	Griffiths and Philippot (2013)
Chlorinated compounds	PCBs, PCP, PVCs, PCDD/Fs	Textile industry, pesticide and herbicide industry, oil industry, pulp and paper production industry, wood preservation industry, plastics, fire-retardants manufacture	It kills microbial species and deteriorate soil quality. It has the potential to accumulate in adipose tissues and cause lethal effects to key organs including kidney and livers	Prosser (2012)
Oil hydrocarbons	Alkanes, alkenes, cycloalkanes	Oil industry	It reduces microbial diversity and abundance which affects soil functionality.	Carson et al. (2010), Valentin et al. (2013)
Volatile organic compounds (VOC)	Benzene, toluene, ethylbenzene and xylenes	Oil industry, gasoline stations, manufactured gas plants	It limits the diversity and distribution of soil bacteria	Griffiths and Philippot (2013)
Nitroaromatics	TNT, nitrobenzene, nitrophenols, atrazine	Aniline factories, dyes, drugs, explosive industry, military facilities, pesticide and herbicides factories	It causes the development of anti-biotic microbes which undergoes mutation overtime and become resistant	Basak et al. (2021)
Perfluorinated compounds	PFOA, PFOS	Aerospace and defence industries, aviation industry, textiles industry, leather and apparel industry, food processing industry, electronics factories and construction and household products sectors.	They are recalcitrant in the environment declining species richness and diversity in intolerant microbial species. They cause liver enlargement, immunotoxicity and reproductive and developmental alterations	Prosser (2012), Gützkow et al. (2012), DeWitt et al. (2012)
Plastics and synthetic polymers	High density polyethylene (HDPE), low density polyethylene (LDPE), poly propylene, polyvinyl chloride (PVCs)	Detergents, plastic bags, clothing, food packs, pipes, cables, water bottles	They penetrate the food chain, and are ingested by aquatic organisms. They disrupt endocrine functions and severely impact organs (e.g. kidneys) when ingested by aquatic organisms	Priya et al. (2022) ;

Asbestos	Amosite, crocidolite, and chrysolite	Construction materials, manufacturing industries, mining sector	Asbestos is hazardous and could lead to malignant tumor in lungs, abdomen or heart	Cheng et al., (2020), Ainagulova et al. (2022)
Radionuclides	Strontium-90, cesium-137, uranium-235, uranium-238, thorium-232, and potassium-40	Improper disposal of radioactive materials, deposition from testing of nuclear weapons and radiological events.	They are toxic, and are easily taken up by plants, animals and humans due to their similarity with calcium. In humans, they accumulate in bones and cause dystrophic changes of the bone and articular system	Salminen-Paatero and Paatero (2021)
Trace elements	Arsenic, lead, nickel, cadmium, mercury and lithium	Fertilizer industry, wastewater and solid waste sectors, fossil fuel combustion, and sewage application	They are toxic even at low concentrations to humans, animals and plants. They cause decline in crop yield due to inhibition of metabolic processes.	Gupta et al. (2019).
Explosives	2,4,6-trinitrotoluene (TNT), hexahydro1,3,5-trinitro-1,3,5-triazine (RDX), and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX)	Military training ranges, ammunition production facilities, wastewater generated from TNT manufacturing	They are persistent and recalcitrant to degradation, toxic and mutagenic	Penning et al. (2022)
Pesticides	Insecticides, fungicides, nematicides, rodenticides and herbicides including DDT, aldrin, heptachlor and toxaphene	Agro-chemical industries, and run-off from applied sites	They are toxic, persistent in the environment and can impact non-target species including humans. They cause biomagnification in food chains	Lee and Choi (2020), Han et al. (2019)
Plasticizers	Bisphenol A (BPA) and phthalates	Plastic additives industry	They are endocrine disruptors that cause toxic effects such as cancer and osteoporosis	Ramakrishna et al. (2022)

Soil remediation is a critical process aimed at restoring contaminated soils to their natural or intended state, making it safe for human and environmental health (Diamond et al., 1999; Bardos et al., 2011; Azuazu et al., 2023; Table 2). The choice of remediation method depends on the type and extent of contamination, site-specific conditions, and the desired remediation goals. Successful soil remediation could contribute to ecosystem rejuvenation and promote sustainable land use and responsible environmental stewardship (Azuazu, et al., 2023).

There have been several techniques and new applications of existing technologies in the field of soil remediation that are contributing to the evolution and change of soil remediation practices (Figure 2).

Existing soil remediation techniques have been improved overtime to enhance their practical application towards addressing soils contaminated by single or multiple contaminants (Song et al., 2022). Recent application of bioremediation has demonstrated in the use of microorganisms to break down contaminants in soil (Song et al., 2022). Newer technologies such as bioaugmentation and biostimulation can be more effective and efficient than traditional methods and can also be more sustainable and cost-effective. For example, bioremediation techniques including microbial remediation, innovatively reduce greenhouse gas emissions and enhance net environmental benefits (Song et al., 2022). The advantages and limitations of each remediation approaches are summarised in Table 2.

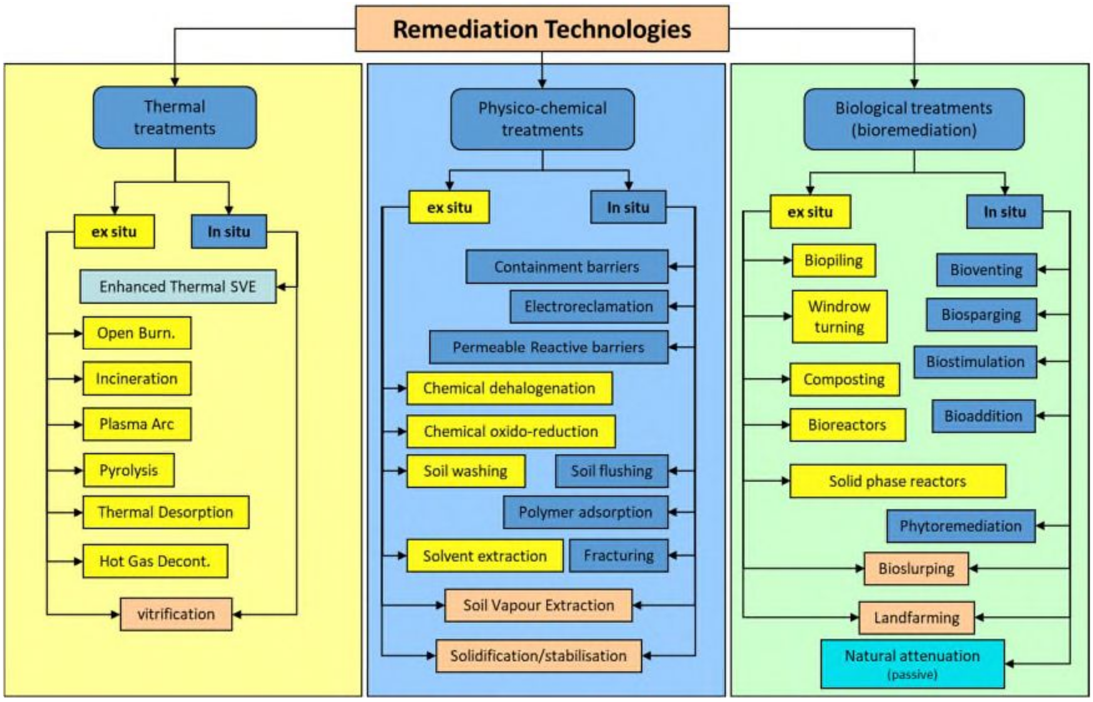

Figure 2. Overview of remediation technologies

A major challenge in soil remediation is the diversity of contaminants present in the soil. Contaminants can be of different types, such as heavy metals, pesticides, organic compounds, and emerging contaminants. These contaminants can co-exist and mutually inhibit each other during remediation processes, making it difficult to address all the contaminants simultaneously. Another challenge is the adsorptive behaviour of contaminants, which enhances their ability to bind to soil sites and modify surface properties. This can make it difficult to remove contaminants from the soil using conventional remediation techniques. In addition, contaminants can impact soil biology, including microbial populations and soil organic matter, which can affect the effectiveness of remediation techniques (Zabbey et al., 2017). In light of these challenges, assessment and prediction of effective remediation techniques can be difficult (Zabbey et al., 2017).

Table 2. Advantages and limitations of remediation methods

Method	Advantages	Limitations	Reference
Phytoremediation • Phytoextraction • Amendment/chelating-agent for phytoextraction • Plant growth-promoting bacteria	• Applied to a wide range of inorganic and organic pollutants; • Environmentally friendly and socially accepted; • Reduce waste amounts entering dumps; • Simple to use and maintain; • Offers lower labor expenditures.	• Limited by the depth, mainly applicable to the top layer of the soil; • Requires a long time but less natural regeneration requires; • There is the possibility of bioaccumulation of pollutants in the food chain; • Suitable only for low-polluted soils; • Amendments and agronomic practice may adversely affect the mobility of pollutants.	Koptsik, 2014; Mohammed and M-Ridha, 2019
Physical-chemical remediation • Soil washing • Encapsulation • Soil Vapour extraction • Electrokinetic • Thermal desorption • Immobilization • Stabilization • Chemical oxido-reduction • Chemical dehalogenation • Air Sparging • Air venting • Nanotechnology	• Increasing the soil environmental capacity; • Short time • Easier to monitor and control; • Can be applied to different types of soils; • Equipment is widely available and simple; • High security; • Moderate efficiency.	• Expensive • Appropriate for micro-regions with severe pollution • Not a permanent solution as heavy metal is released into the soil under weathering conditions • Needs large amount of binder • Volatile organic compounds and some particulates may come out during treatment process • It has potential to contaminate other environmental media, such as air and water bodies, throughout the remediation process.	Gan et al., 2009; Yao et al., 2012; Cappuynes, 2013; Zabbey et al., 2017; Peng et al., 2021; Garcia-Segura et al., 2020 ; Hussain et al., 2022.

Bioremediation • Biostimulation • Bioaugmentation • Bioadmendment • Landfarming • Biopiles/windrows • Monitored natural attenuation	• Natural ability of microorganisms • Less energy is required • Cost-effective technique • Enhanced regulatory and public acceptance • Soil stabilization and reduced water leaching and transport of organic compounds in soil • Generate small amount of waste • No residual environmental impact or risk	• High constituent concentrations may initially be toxic to microorganisms • Not applicable for certain site conditions such as low soil permeability • Limited to low contamination areas • Moderate efficiency • Not useful for treatment of inorganic contaminants or every organic compound • The incorrect supply of nutrients might have adverse effects on the ecosystem. • Time consuming	Wu et al., 2008; Eze et al., 2018; Kumar et al., 2018; Peng et al., 2021
Photo-catalytic treatments • Photocatalytic degradation	• It is possible for several forms of contaminants, particularly in mixed contaminated media	• Highly reliant on power supply, which may be difficult in some setting	Zhang et al., 2008
Thermal treatments • Injection of stream of hot air • Incineration • Soil vapour extraction • Thermal desorption • Pyrolysis • Plasma arc • Vitrification	• High efficiency • Can recover about 99% of volatile and semi-volatile contaminants • Reduces uncertainty and encourages aerobic biodegradation of contaminants • Short time	• There is a high possibility of displacing contaminants by the injection fluid, to areas that are not the recovery points • Expensive and consumes a lot of energy • Useful only for treatment of volatile contaminants • High environmental impacts	Acharya and Ives, 1994 ; Meghanaj et al., 2011 ; Kuppusamy et al., 2016

To address these challenges and issues of mixed contaminants in soil, a remediation treatment train, (i.e. a combination of technologies used in sequence or in parallel) is often required, to effectively clean up contaminated soil. The selection of technologies depends on various factors such as the type and extent of contamination, soil characteristics, environmental conditions, and regulatory requirements. (Dadrasnia and Agamuthu, 2014). For example, a combination of physical, chemical, and biological treatments may be used in a treatment train to remediate soil contamination. Excavation or Soil Vapor Extraction (SVE) (physical treatments) can be used to remove or extract contaminants from the soil. Chemical treatments such as oxidation or reduction can be used to transform or degrade contaminants. Biological treatments such as bioremediation can be used to utilize microorganisms to break down or transform contaminants into less harmful forms.

The use of a treatment train can help address the complexity of soil contamination and the challenges associated with remediation, such as the presence of multiple contaminants and the need to meet sustainability requirements. An example of the integration of remediation techniques is reported in Amin et al. (2014) to demonstrate the efficacy of remediation treatment train. The study integrated bioventing and SVE at a lab-scale and demonstrated efficiency in the removal of over 99.5% of potentially toxic elements (PTEs) after 96 hours of air injection at a constant flow rate of 250 mL/min. This indicates that physical and chemical remediation approaches could be integrated to achieve better efficiency and reduced net environmental impact. It is suggested that bioremediation be integrated as a step in most remediation activities, as the allows the environment to rejuvenate and provides opportunities for biodiversity restoration (Zabbey et al., 2017; Michael-Igolima et al., 2022; Nwankwegu et al., 2022). However, the use of a treatment train can also increase the cost and complexity of remediation, and the effectiveness of the treatment train must be carefully evaluated and optimised to achieve the desired result (Angyal, 2008; Xia et al., 2019; Zhang et al., 2019; Michael-Igolima et al., 2022). Among the established technologies, some of them require extensive use of water, energy and chemicals which significantly increase the cost and difficulty of the treatment process, and potentially reduce the applicability and practicability (Lu et al., 2020, Figure 3).

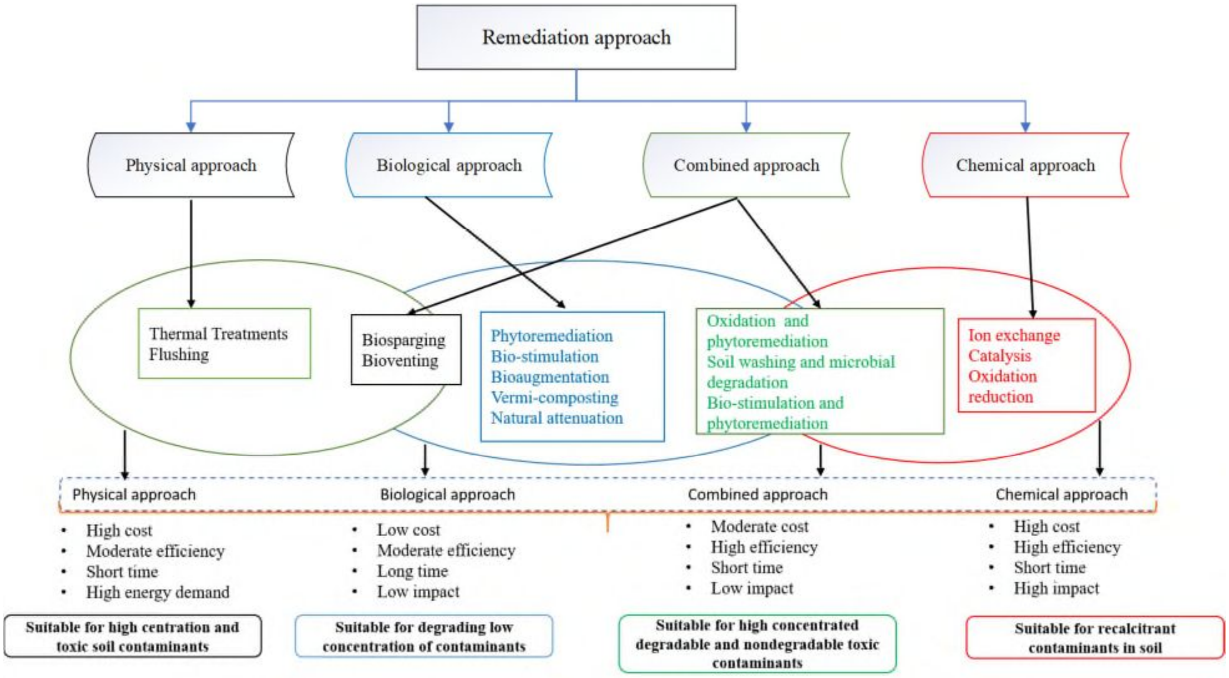

Figure 3. Comparison of different remediation approaches (Adapted from Michael-Igolima et al., 2022). An illustration of the different remediation techniques that could be considered for a remediation treatment train depending on remediation objectives, type of contaminant and available resources.

Thus, remediation practices and combinations of treatment trains continue to evolve following innovations and technological advancements in the remediation practice. Some of the development in sustainable remediation are briefly outlined below:

Advancements in metagenomic analysis indicates specific microbial metabolic pathways involved in contaminant breakdown, which facilitates the development of contaminant-specific bioremediation strategies (Azuazu et al., 2023). In addition, new developments have shown microbial efficacy to remediate emerging contaminants such as per- and polyfluoroalkyl substances (PFAS) and microplastics, which has expanded the capacity of sustainable remediation approaches such as bioremediation (Mayakaduwage et al., 2022). Newer technologies such as bioaugmentation (e.g., introduction of contaminant-degrading bacteria remarkably increases the biodegradation process) (Muter, 2023), and biostimulation can be more effective and efficient than traditional methods and can also be more sustainable and cost-effective (Mayakaduwage et al., 2022; Azuazu et a.l 2023). For instance, advancements in biostimulation including the integration of sustainable materials such as biochar (Azuazu et al., 2023), which is a slow-release nutrient source, enhances the sustainability and efficacy of bioremediation techniques (Nwankwegu, et al., 2022; Sim et al., 2021).

Use of nanotechnology: Nanotechnology is being used to develop new remediation technologies that can target contaminants more effectively and with fewer negative impacts on the environment. For example, nanoparticles can be used to remove heavy metals and organic pollutants from contaminated soil (Sam et al., 2023).

Phytoremediation: Phytoremediation, which involves the use of plants to remove contaminants from soil, is another emerging technology that has the potential to be more sustainable and cost-effective than traditional methods. Researchers are working to identify and optimize the use of plants for phytoremediation in different types of soils and contaminants (Wang et al., 2021).

In-situ remediation: In-situ remediation, which involves treating contaminants in place without excavating soil, is becoming increasingly common. This approach can be more cost-effective and can minimize disruptions to the environment and local communities (Song et al., 2022).

Electrokinetic remediation: Electrokinetic techniques use electrical fields to enhance the removal of contaminants from soil. Although research is currently focused on improving the energy efficiency and scalability of electrokinetic remediation processes. Integration with renewable energy sources and the development of more effective electrode configurations can make this method more practical for large-scale soil remediation projects (Hussain et al., 2022).

Integration of artificial intelligence and machine learning: Artificial intelligence and machine learning are used to improve the accuracy of contaminant detection, predict contaminant behaviour and movement, and optimise remediation strategies. This can lead to more effective and efficient soil remediation (da Silva Medeiros et al., 2022). We recognize that many sites are often contaminated by mixed contaminants requiring decisions on remediation treatment train. In this article, we emphasized a combination of remediation approaches that reduce emission of greenhouse gases, least impact on natural resource, considers cost effectiveness, returns net environmental benefits and restores the site as soon as practicable. As a result, depending on the contaminant, remediation objectives and resources available, sustainable remediation may require decision on a combination of techniques.

Overall, these new developments in soil remediation are contributing to the evolution and change of soil remediation practices providing more effective, sustainable, and cost-effective solutions. As these technologies advance, we can expect to see continued improvements in soil remediation practices, leading to cleaner and healthier environments for all.

3. Environmental impacts of soil remediation

One of the most debated aspects of soil remediation treatments is their environmental sustainability. Commonly, three types of environmental impacts (primary, secondary and tertiary) are recognized in a contaminated site (Sparrevik et al., 2011). The primary impacts are associated with the environmental impacts caused by the on-site contamination; the secondary ones are usually related with the intervention at the site, such as the remediation process; and the tertiary impacts are connected to possible post-remediation activities, such as the development of a greenfield (Søndergaard & Owsianiak, 2018). LCA is a well-known methodological approach capable of quantifying environmental impacts of products and processes (ISO 14040, 2006). Usually, LCA is used to quantify secondary and tertiary impacts. Sometimes from an LCA consequential perspective, some assumptions need to be done and those may be straddling primary, secondary, and tertiary stages. Several remediation studies in the literature involve the use of LCA to assess and compare the environmental feasibility of different soil remediation technologies. Current practices for evaluating sustainable soil remediation technologies using LCA typically involve the following four-step process (ISO 14040, 2006): i) goal and scope definition, specifying the purpose of the study, the system boundaries, and the functional unit (e.g., amount of contaminated soil remediated); ii) Life Cycle Inventory (LCI), which involves the collection of data on the inputs and outputs of the remediation process, including energy and material flows, emissions, and waste; iii) Life Cycle Impact Assessment (LCIA), which involves the evaluation of the environmental impacts of the remediation process; iv) interpretation, to analyse the results and draw the main conclusions. It is ideal to perform remediation in a closed-loop system, with a conservation of the site characteristics, including soil, water bodies, and the entire ecosystem. The availability of data is a crucial point. Primary data, such as suppliers' data for materials and energy flows, are not always available and official databases or scientific literature are often considered (secondary data) (Labianca et al., 2022).

Sometimes the main scope is to identify which of the in-situ and the ex-situ approach is more sustainable (Hu et al., 2022). Table 3 collects the main LCA studies applied to soil remediation in literature based on the keywords “LCA” and “soil remediation technologies” in the time frame 2013-2023. Pranjić et al. (2018) found that the in-situ soil remediation method resulted in significantly lower impacts on human health and ecosystem categories (based on the ReCiPe end-point approach) (Huijbregts et al., 2016) than the no-action scenario. On the other hand, the ex-situ scenario, despite the recovery of valuable metals from the incineration bottom ash, was much more environmentally burdensome due to the high fuel consumption during the incineration process. One of the most important pioneering directions is Green and Sustainable Remediation (GSR). It refers to the maximization of the Net Environmental Benefit (NEB) by analyzing not only the environmental benefit but also the environmental life-cycle costs of remediation operations (Hou et al., 2017). In this regard, Vocciante et al. (2019, 2021) studied the carbon footprint of a phytoremediation treatment of heavy metals contaminated soils using *Brassica juncea, Lupinus albus, and Helianthus annuus* plants. To reduce the overall impact of the treatment, they further incinerated the biomass to obtain energy and reduce the environmental impact by approximately 29%, while also avoiding the biomass disposal phase. The same approach was proposed by Todde et al. (2022), who applied *Cannabis sativa L.* for the phytoremediation of polluted soils and recovered energy from the incineration of the biomass. Espada et al. (2022) compared phytoextraction treatment with subsequent biomass disposal and/or energy recovery with soil excavation (physical) and soil washing (chemical) treatments. As a result, they highlighted that the use of *F. Arundinacea* phytoextraction with energy recovery appears to be an attractive option for sustainable remediation of highly Pb-contaminated soil. However, this technique can only move impacts from one system to another, because the biomass burnt in the combustion chamber can release heavy metals into the environment as ash or fly ash in the flue gas (Vocciante et al., 2021).

It is essential to define the functional unit (FU) that will serve as the reference unit for assessing environmental impacts. The FU can vary significantly with the scope and the scale; an ad hoc evaluation is always recommended. The most common FU in literature is the total volume of contaminated soil to clean-up over a given time period (Table 3). However, it is difficult to compare the results from different studies as different system boundaries are used (Owsianiak et al., 2013). An example of typical LCA system boundaries is shown in Figure 4.

The materials involved in the remediation play a central role on the overall impacts. Gallagher et al. (2013) and Hou et al. (2016) used cement as the main material in the remediation project and the LCA highlighted the extremely high impacts associated with it, as recognized globally (Labianca et al., 2023). In contrast, biochar scored the lowest impacts as a material used in the S/S treatment due to its pyrogenic carbon storage and sequestration (PyCCS) (Woolf et al., 2021). Different authors calculated a range of 2–2.6 kg CO_2eq to be associated with PyCCs for every kg of biochar used (Azzi et al., 2019; Gupta, 2021; Woolf et al., 2021).

The solid waste and wastewater produced during the overall duration of the remediation treatment also play a significant role in the development of an LCA. In Busset et al. (2012), wastewater was subsequently treated with lime and flocculating agents, involving the use of other materials and energy, while solid residues from incinerated soils and sludge from gas scrubbing were sent to a hazardous waste landfill, burdening the overall impacts and costs. Several tools and software are available to users to develop comprehensive assessments in which the type of produced waste and its management can also be included. The environmental impacts from the disposal of materials involved in the treatment, such as activated carbon, chemicals, cement, etc., are not always taken into account. Therefore, the cost and impacts associated with the management and disposal of spent materials should always be part of the system boundaries (Figure 4). In literature, the system boundaries usually vary among cradle-to-site, site-to-site, cradle-to-grave, and cradle-to-cradle approaches (ISO 14040, 2006). Most of studies have considered a cradle-to-grave approach, including each subsequent stage of manufacturing, transportation, product use, and ultimately, disposal. Table 3 shows that ReCiPe is the most widely used methodology with a broad range of midpoint and endpoint impact categories. Only two studies (Todde et al., 2022; Vocciante et al., 2019) used a single impact method analysing global warming.

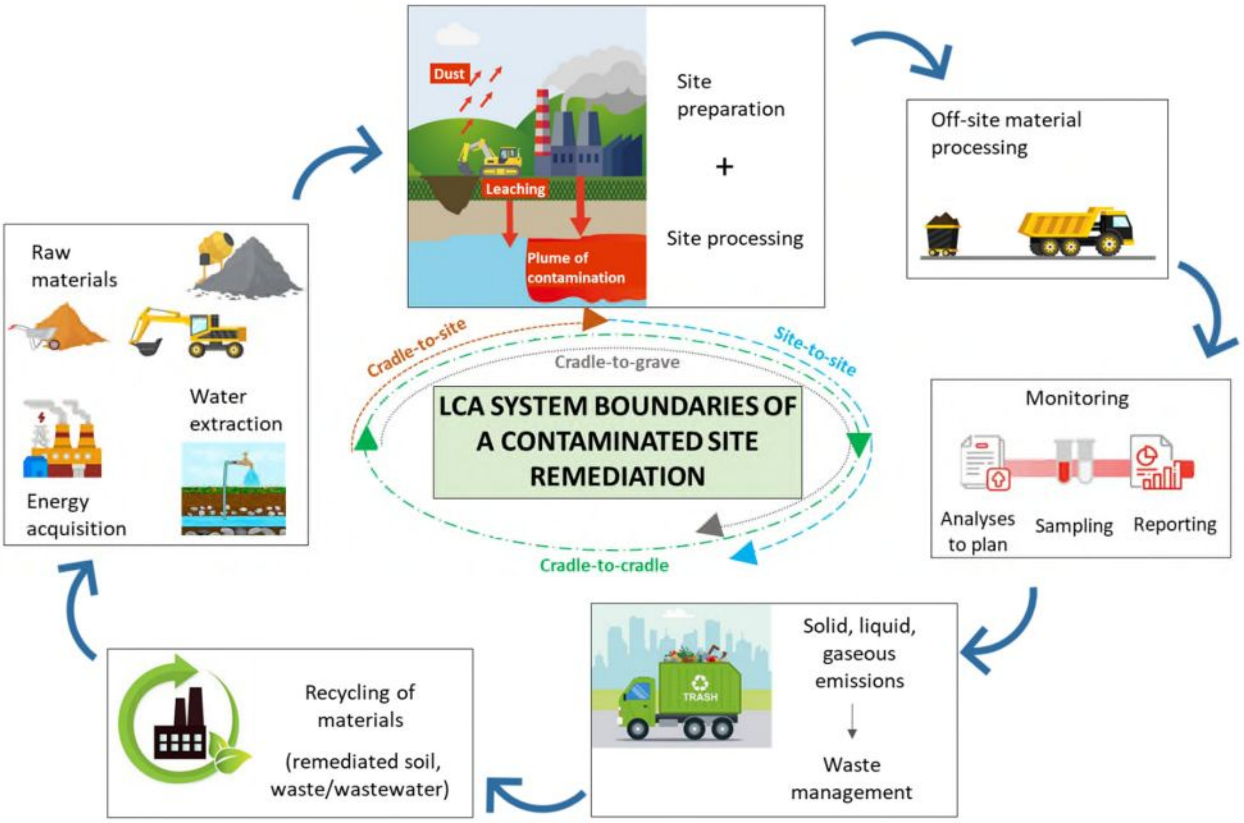

Figure 4. Typical LCA system boundaries of a contaminated site remediation.

In summary, the use of LCA to evaluate sustainable soil remediation technologies has several limitations and opportunities, such as:

1) Data related to primary and tertiary impacts are not always included in LCA. Mostly secondary impacts are assessed in LCA literature studies. Sometimes from an LCA consequential perspective, some assumptions need to be done and those may be at the interface among primary, secondary and tertiary stages.

2) LCA requires comprehensive and accurate data on the environmental impacts of the remediation process, but contaminated sites can be complex and involve multiple remediation stages and processes, which can make it challenging to accurately model and assess the total environmental impacts, especially if only secondary data is used;

3) LCA can help identify opportunities for improving the sustainability of soil remediation technologies, such as reducing energy consumption, minimizing waste generation, or using renewable resources. Allocation is one common strategy for solving multi-functionality problems. However, to prevent burden shifting, a full life cycle should be always considered;

4) LCA is overall complex and requires an understanding of impact assessment methods and related software. To better meet the SDGs, it is recommended to consider it as a complementary tool to the remediation design to be used for the selection of the best soil remediation alternative from an environmental perspective.

Table 3. Literature overview of LCA-based case studies

Technology	Target pollutants	Functional Unit (FU)	Methodology/ Database	Impact categories	Main results	Reference
1) In situ Multiphase Extraction (MPE), 2) Excavation and ex situ soil treatment	Mix of organic pollutants (benzene, toluene, ethylbenzene, xylene, polychlorinated biphenyls, phenols, chlorinated volatile compound, cresols, mineral oil)	The removal of 80% of 500 metric tons of contaminant mass from a subsurface soil of 40,000 m^3 volume	ReCiPe. Ecoinvent	ReCiPe midpoint indicators	A trade-off exists between greenhouse gas emissions and land availability. All ReCiPe impact categories are affected more by excavation; however, excavation yields the benefit of a resource becoming available sooner.	(Beames et al., 2015)
1) In situ phytoremediation and biogas production 2) In situ phytoremediation and Landfill 3) Ex situ excavation and landfill	Lead	One hectare of decontaminated land	ReCiPe. Ecoinvent	ReCiPe midpoint and endpoint indicators	The use of phytoremediation to recover heavy metal-contaminated soils can provide a sustainable benefit. In phytoremediation, synthetic natural gas production is an important component to achieving sustainability, as it prevents fossil fuel depletion in the process of rehabilitating contaminated land.	(Vigil et al., 2015)
Thermal desorption, 2) stabilization/solidification	Mercury	1 tonne of mercury contaminated topsoil in agricultural land to	ReCiPe. Ecoinvent	Ecosystem, human health, and resources (endpoint)	The conventional high temperature desorption resulted in 357 kg CO_2eq of GHGs, whereas S/S with coal-based powdered activated	(Hou et al., 2016)

		meet regulatory standards.			carbon (PAC) resulted in 365 kg CO_2eq of GHGs per tonne of contaminated treated soil. The innovative acid-facilitated low temperature desorption technique reduced GHGs to 264 kg of CO_2-eq due to a reduced energy consumption. S/S with biochar-based PAC reduced GHGs to 105 kg CO_2-eq thanks to carbon sequestration during the biomass pyrolysis.	
Flue gas desulfurization gypsum-based (FGDG) treatment	Saline-sodic soil	1 ha saline-sodic soil	TOPSIS+CML. Direct/measured data	Energy consumption, Water consumption, Global warming, Acidification, Eutrophication, Soil toxicity, Photochemical ozone, Human toxicity, Water toxicity	The application of FGDG contributed 42.216% and 15.429% on water consumption and soil toxicity, respectively. The impacts on acidification, eutrophication and water toxicity were comparatively low.	(Li & Wang, 2018)
Excavation with off-site thermal treatment	Tar, PAH and cyanide	2555 m^3 of contaminated soil	ReCiPe. Ecoinvent	Human toxicity, Respiratory inorganics, Ionizing radiation, Ozone layer depletion, Ecotoxicity, Nature occupation, Global warming, Acidification, Eutrophication, Respiratory organics, Photochemical ozone, Non-renewable energy, Mineral extraction	The impact categories that most contribute to the secondary environmental impact of the remediation are fossil depletion, climate change and formation of particulate matter. Cleaning of the contaminated soil in off-site facilities had the highest environmental impact of the remediation project (70% of the total impacts). The high amount of fossil fuels and energy used was the main cause.	(Huysegoms et al., 2018)
1) Incineration, metal extraction, underground disposal and reclamation of the site by refilling it with replacement	As, Cd, Cu, Ni, Pb, Zn and PAHs	1 m^3 of contaminated soil	ReCiPe. "Professional and Extensions" Database from GaBi	ecosystem, human health, and resources (end-point)	The in-situ soil remediation conducted by immobilizing the hazardous substances in the soil using an additive is significantly more sustainable than	(Mauko Pranjić et al., 2018)

material, 2) underground disposal and reclamation of the site by refilling it with replacement material, 3) no action (NoA)					the other two alternative scenarios discussed. As expected, the most significant benefit is related to the reduction of the impact on the consumption of resources, but the impacts on the ecosystem and human health are also significantly smaller than those in the other two discussed scenarios	
Nano-scale zero-valent iron (nZVI) production methods: 1) iron milling, 2) Liquid chemical reduction with sodium borohydride, and 3) chemical reduction with hydrogen gas	-	1 kg of nZVI produced	Impact 2002 +. Ecoinvent	ecosystem, human health, and resources (end-point) + climate change	Based on the results of the LCA and LCC, reduction with sodium borohydride is the method with the best environmental performance and the milling method is the one with the best economic performance.	(Visentin, Trentin, et al., 2019)
1) In situ encapsulation (ISE), 2) ex situ thermal desorption (ESTD), 3) in situ thermal desorption (ISTD)	VOCs, SVOCs, and heavy metals	1.25091 million m^3 of contaminated soil	IO-LCA model	production and supply of gas (PSG), production and supply of electric power and heat power (PSE), special purpose machinery (SPM), petroleum and natural gas extraction (PNG), coal mining and dressing (CMD), chemical products (CMP), and nonmetallic mineral products (NMP)	ISE technology had the lowest cost and the best environmental impact, but it is recommended for deep contaminated soils only. ISTD was the best technique in the comprehensive evaluation. ISE – ESTD were the most suitable alternatives.	(Chen et al., 2020)
1) Phytoremediation + biomass management as A) disposal in a security landfill, B) energy recovery, 2) soil washing, 3) excavation + landfill	Pb	1 ha of contaminated soil (at a depth of 20 cm) up to the maximum Pb concentration allowed by the government regulations, which	CML 2001. Gabi database (not specified)	Global warming potential, Acidification, Eutrophication, Human toxicity	The combination of phytoextraction + energy recovery reduced the total impacts in all the categories compared to direct biomass disposal thanks to the avoided impacts by electricity and heat production. Concerning the traditional methods, the production	(Espada et al., 2022)

		means 3000 tons of contaminated soil			of hydrochloric acid had the highest impact for soil washing treatment. Instead, soil disposal was the highest contribution for excavation+landfill treatment.	
1) In-situ containment, 2) in-situ containment+ex-situ thermal desorption, 3) ex-situ thermal desorption, 4) in-situ thermal desorption	VOCs, SVOCs, and mercury	1000 m^3 of contaminated soil to meet the risk-based remediation targets	ReCiPe. Ecoinvent	ecosystem, human health, and resources (end-point)	Alternative 4 scored the highest environmental and economic impacts because of extensive use of in-situ thermal desorption, followed by Alternatives 1, 3, and 2.	(Hu et al., 2022)
Phytoremediation+energy production from burning biomass	Heavy metals	1 kg of dry matter industrial hemp product and 1 ha of phytoremediated area	IPCC 100y. Ecoinvent	Global warming	Among the 4 designed scenarios with industrial hemp supply chain, the best systems saving high amounts of energy included anaerobic digestion and/or incineration of the biomass.	(Todde et al., 2022)

4. Opportunity for resource recovery from contaminated soil

Resource recovery from contaminated soil is an emerging area of research that seeks to maximize the use of resources contained in contaminated soil while offering sustainable solutions to mitigate environmental pollution. This approach aligns with the principles of sustainable remediation practices, the emerging EU Soil Health law, and the United Nations Sustainable Development Goals (SDGs).

Opportunities for resource recovery from contaminated soil can include i) extraction of valuable metals, ii) production of biofuels, iii) production of amendment, and iv) bioremediation.

Extraction of valuable metals: Contaminated soil may contain precious metals such as copper, zinc, and nickel as most metals are highly retained by soils, which can be extracted by techniques such as phytomining, bioleaching, or electrochemical methods (Cajuste et al., 2000; Potgieter-Vermaak et al., 2019; Li et al., 2020; Minut et al., 2021; Sur et al., 2022).

Biofuels production: Contaminated soil can be used to grow energy crops such as switchgrass, willow, or poplar, which can be converted into biofuels using processes such as pyrolysis, fermentation, or gasification (Van Ginneken et al., 2007; Kokyo et al., 2013; Balsamo et al., 2015; Dastyar et al., 2019; Grippi, 2021).

Soil amendment production: Contaminated soil can be treated to remove contaminants and then used as a soil amendment, providing nutrients and organic matter to improve soil health (Bolan et al., 2014; Lwin et al., 2018; Palansooriya et al., 2020).

Bioremediation: Microbial degradation of contaminants in contaminated soil can lead to the production of methane, which can be captured and used as a renewable energy source (Gaspard and Ncibi, 2013; Pimmata et al., 2013; Wang et al., 2021; Wang et al., 2022).

Sustainable remediation practices, the EU Soil Health Law initiative, and the SDGs provide a framework for assessing the environmental and social impacts of resource recovery from contaminated soil (Orner et al., 2018). These approaches prioritise the protection of human health and the environment, the promotion of social equity, and the responsible use of natural resources. By incorporating these principles into the design and implementation of resource recovery strategies, it is possible to promote sustainable development while also addressing the challenges of contaminated soil management.

As mentioned above, contaminated soil is a problem due to the presence of heavy metals, rare earth elements, petroleum, and various organic contaminants. However, these contaminants can be extracted and reused, thus addressing the problem through secondary use and biotransformation. For example, polyhydroxyalkanoates, volatile fatty acids, cellulose and radionuclides are retrieved from various sources of waste or contaminated soil, which can be utilized for medicine catalysis in cosmetics and electronics (Yadav et al., 2021).

Heavy metal pollution is a significant global environmental problem due to its toxicity, long persistence, and bioaccumulation (Liu et al., 2016). Remediation technologies, such as ion exchange and chemical precipitation, have been employed to immobilize and transform heavy metals into less toxic forms (Azimi et al., 2017; Zamri et al., 2017). Nonetheless, demonstrating economic viability and environmental impact remains a challenge for many of the existing remediation technologies. Heavy metals are present in soil at high concentrations and can have an impact on plant growth and development, soil fertility, and microbiota. Plants have different response patterns towards heavy metals in soils (Wang et al., 2021). The phenomenon of hyperaccumulation, wherein usually high concentrations of heavy metals are accumulated in plant tissues (Wang et al., 2021), is associated with a strongly enhanced ability to detoxify the metal accumulated in above-ground tissues, and thus, with metal hyper-tolerance. Hyperaccumulator plants can accumulate metal to a truly remarkable level. Phytomining is a promising application of the hyperaccumulation phenomenon, which involves the extraction of contaminated soil with plants, followed by the recovery of valuable heavy metals from plant biomass (Minut et al., 2021). The key aim of phytomining is to clean contaminated soil, which threatens the environment and human health. Additionally, it offers the possibility of recovering heavy metals from plant biomass using various techniques. Therefore, phytomining can be an excellent tool for recovering metals while providing suitable approaches for contaminated soil. However, this approach requires a better understanding of the molecular mechanisms of metal uptake, tolerance, accumulation and translocation (Wang et al., 2021).

Contaminated soil often contains rare earth elements (RREs) which are crucial components of high-tech electrical and electronic-based materials and essential for achieving a carbon-dioxide-neutral society (Dodson et al., 2012; Jyothi et al., 2020). However, the low concentration of RREs in the soil makes its economic recovery difficult. Several factors, including soil layers, pH, clay minerals, and organic matter, influence the concentration of RREs in the soil. A way to improve the leachability of RREs is the use of using humic acids (Lee et al., 2022).

Remediation of contaminated soil and recovery of valuable resources can also be achieved through soil washing, a widely adopted technique (Islam and Chatterjee, 2021). This method involves the use of water or other solvents to dissolve or mobilize the contaminants in the soil, followed by the separation of the contaminants from the soil by physical or chemical methods. The resulting soil can be reused, and the recovered contaminants can be recycled or disposed of safely.

Soil washing has been successfully employed for the removal of various contaminants, including heavy metals, pesticides, and petroleum hydrocarbons (Liu et al., 2017; Cao et al., 2018; Khan et al., 2020). However, the efficiency of soil washing depends on factors such as the type of contaminants, soil properties, and washing solutions used.

An excellent example of the effectiveness of soil washing is the remediation of contaminated soil at a former industrial site in Belgium, where heavy metals were removed, and valuable metals such as zinc, copper, and lead were recovered (Van Gerven et al., 2018). The recovered metals were sold for recycling, while the cleaned soil was reused on-site.

Soil washing has many benefits over traditional remediation methods, such as a faster process, minimal excavation, and the recovery of valuable resources that would have been lost (Islam and Chatterjee, 2021). Nevertheless, it is essential to note that soil washing may not be appropriate for all types of contaminants or soils. For example, employing acid washing can alter soil characteristics and produce a substantial amount of liquid that necessitates treatment before it can be safely released. Furthermore, acid washing might pose difficulties when dealing with soils abundant in carbonate compounds (Juang and Wang, 2000). Lee et al. (2023) proposed that in situ metal recovery from landfills is a novel technology that offers sustainable remediation approaches for contaminated soils. Leachate recirculation can significantly influence the behaviour and fate of metals within landfills. The solubility of metals increases significantly at the beginning of recirculation and then decreases (Lee et al., 2023). This process can be divided into two parts: soil remediation and metal recovery (details in Supplementary data Fig. S2).

In order to increase the metal recovery rate and effectively wash contaminated soil, a suitable extractant, such as nitrilotriacetic acid (NTA), citrate or ethylenediaminetetraacetic acid (EDTA), is required (Juang and Wang, 2000). However, the elevated cost of agents like EDTA can preclude their utilization in recovering metals from metal-contaminated sites. Also, EDTA does not biodegrade rapidly, and its persistence magnifies concerns about its effects (Davis and Green, 1999).

These problems lead to the search for effective treatment processes. Therefore, many different chemical species, including acids, bases, salts, oxidizing or reducing agents, chelating agents, surfactants, and solvents, have been developed for separating contaminants from the contaminated soil for washing techniques (Begum et al., 2016). Methane is a potent greenhouse gas produced by the anaerobic decomposition of organic matter in contaminated soil. Instead of allowing methane to escape into the atmosphere, it can be captured and used as a renewable energy source during the remediation of contaminated soil (Ozbay et al., 2021). The use of methane from contaminated soil as a renewable energy source provides multiple benefits. It offers a sustainable source of energy that helps reduce greenhouse gas emissions, provides a financial incentive for remediation, and reduces the risk of methane emissions, which can pose safety hazards in contaminated areas such as landfills (Sousa et al., 2021). It is crucial to emphasize soil remediation technologies focusing on resource recovery to achieve a sustainable and circular economy. However, several factors should be considered for further research, as they might pose challenges in recovering resources from contaminated soil. The factors to consider are: i) contaminated soil encompasses a diverse spectrum of pollutants, thereby accentuating the intricacy of the contaminants present; ii) soil composition varies significantly from one location to another. Therefore, heterogeneity in soil properties can affect the mobility and distribution of contaminants, making it challenging to design effective recovery methods; iii) separating and purifying selective resources will be challenged if contaminants are closely intertwined with the desired resource and iv) it is crucial to ensure the sustainability of resource recovery, which consider the potential for recontamination and the ecological impacts of resource recovery. Overall, additional research is essential to develop remediation techniques that can effectively and efficiently clean contaminated soils while extracting valuable metals and recovering energy, which can contribute to the circular economy.

5. Holistic approaches to connect environmental, economic and social aspects

A wide variety of techniques have been employed in sustainability assessment frameworks and tools, including LCA, cost-benefit/effectiveness analysis, health risk assessments, multi-criteria decision analysis, streamlined versions such as environmental ecological and footprint analyses, and social evaluations (Hu et al., 2022). However, it is often challenging to combine all the information related to a remediation project together. Practitioners should aim to integrate data on risk assessment, environmental sustainability, costs, and social acceptance in a more holistic way. In this regard, several new tools are available to integrate sustainability into soil remediation practices. Hou et al. (2017) combined LCA and health risk assessment to create a more robust decision-making tool. By combining LCA and fuzzy synthetic evaluation (FSE) model together, Hu et al. (2022) aimed to help practitioners in the selection of the optimal remediation plan. They considered 32 indicators on the basis of ten criteria and used FSE to process the results of a questionnaire for the remediation plan of an industrial site contaminated with organic chemicals and mercury. The alternative with extensive use of thermal in-situ desorption had the highest environmental and economic impacts, followed by the scenarios of in-situ containment, ex-situ thermal desorption, and in-situ containment + ex-situ thermal desorption. It is important to consider social implications when analyzing the sustainability of remediation processes. Remediation processes have a variety of effects on society, both on an individual and institutional level (Visentin et al., 2019). It is important to engage the community in the development and implementation of resource recovery strategies to ensure that their needs and priorities are considered.

In the study by Huysegom et al. (2018), the results of the attributional LCA were monetized by using two different techniques, specifically Stepwise 2006 and Ecovalue 08. They also performed a social Cost-Benefit Analysis (s-CBA) on the same case study concerning the remediation of soil and groundwater from tar, PAH and cyanide contamination of a school ground. The best remediation treatment identified was excavation with off-site thermal treatment and the s-CBA showed that the project can be socially beneficial in the long term. Thus, decision-makers can obtain a completer and more detailed picture of the remediation plan when multiple assessments are combined. A methodology, namely RNsoil, was proposed by Inoue & Katayama (2011) and integrated the two so-called rescue numbers to evaluate the increased economic costs and environmental impacts on resource depletion on the one hand, and on risk reduction on the other. As part of this model, LCC and economic input–output assessment have also recently been introduced. It is becoming common to integrate LCA, LCC, and social-life cycle assessment (s-LCA) results into one framework (Zhang et al., 2021), but there are not many applications to soil remediation in the literature (Visentin et al., 2019, 2021). In environmental management frameworks, LCA is often integrated with Environmental Risk Assessment (ERA). The former is useful for assessing impacts on a macro (global) scale, while the latter is useful on a micro (local) scale (Liu & Ramirez, 2017). ERA compares the responses of ecological systems to specific stressors such as single chemicals, mixtures, or multiple stressors in a specific realistic worst-case scenario (Muazu et al., 2021). In contrast, LCA usually does not consider background concentrations and cannot address threshold quantification. Another interesting approach is to perform a preliminary screening of remediation technologies by applying the BATNEEC (best available technique not entailing excessive costs) method (Cappuyns & Kessen, 2012) or Multi-Criteria Decision Analysis (MCDA) (Labianca et al., 2020, 2021), followed by a detailed environmental sustainability and cost analysis. The MCDA method called Sustainable Choice of Remediation (SCORE) and developed by Rosén et al. (2015) incorporates environmental, economic, and social aspects of different remediation alternatives. It consists of selecting key performance criteria and involving the stakeholders in the selection of the key sustainability evaluation criteria. A new MCDA method has been introduced by Søndergaard et al. (2018) that incorporates the effects of remediation (on groundwater, surface water, soil, air, etc.) and the time of remediation (to achieve the remedial goals) together with the three pillars of sustainability (social, economic, and environmental). A similar framework has been proposed by Trentin et al. (2019) to strengthen the decision-making process in the selection of the most sustainable remediation technology. In particular, an Integrated Value Model for Sustainable Assessment (MIVES) (Josa and Alavedra, 2006) and an Analytic Hierarchy Process (AHP) have been used together to calculate the Quantitative Assessment of Life Cycle Sustainability (QUALICS). Recently, the Triple Bottom Line sustainability assessment framework has been proposed to quantify the sustainability of remediation projects (Reddy and Kumar, 2019). This framework firstly involves the identification and quantification of the key environmental, economic, and social aspects based on existing sustainability assessment tools. Further, an overall sustainability index is calculated for each alternative by using the MIVES methodology.

The Sustainable Remediation Forum (SURF) Metrics (Smith, 2019) is a well-adopted framework in the UK that helps practitioners assess the sustainability of remediation activities. It includes a set of broad indicators (15 "headline" categories) to support sustainability when assessing soil remediation appraisal (Bardos et a., 2018). It has been used to guide decision-makers and it has influenced the development of other national and international guidance and standards on sustainable soil remediation. Some of the most used voluntary guidelines are those provided by the Global Reporting Initiative (GRI) (Etzion and Ferraro, 2010) and Sustainability Accounting Standards Board (SASB) (Hales, 2021). However, given the complexity of contaminated sites and the specific and interrelated nature of soil degradation, sustainability reporting is not always trivial.

A key challenge is the quantification of sustainability impacts and their disaggregation at the level of individual actors (Gray, 2010). However, these tools are sometimes partially qualitative, making the analysis in part subjective. Labianca et al. (2021) proposed the eDPSIR (engineered-Drivers-Pressures-States-Impacts-Responses) framework with the aim to support the decision-makers in designing remediation solutions and quantify cause-effect relationships in coastal contaminated areas.

Table 4. Main techniques used in literature to connect environmental, economic, and social aspects in a remediation project

Techniques used/combined	**Applications**	**References**
RNsoil	Farmland contaminated with dieldrin	Inoue & Katayama, 2011
BATNEEC (best available technique not entailing excessive costs) method	Brownfield with former oil and fat processing plant	Cappuyns & Kessen, 2012
Sustainable Choice of Remediation (SCORE) - MCDA method	Various remediation projects, differencing in location, setting, type of pollutants, area of concern.	Rosén et al. 2015
LCA + environmental risk assessment (ERA)	Underground exploitation activities	Liu & Ramirez, 2017
LCA + health risk assessment	Pb contaminated soil	Hou et al., 2017
Sustainable Remediation Forum (SURF) Metrics	Contaminated land	Bardos et al., 2018; Smith, 2019
Stepwise 2006, Ecovalue 08 + s-CBA	A former gas plant site	Huysegom et al., 2018
Multi-criteria assessment (MCA) method	Severely polluted site (Groyne 42)	Søndergaard et al. 2018
Triple Bottom Line sustainability assessment framework	Several case studies	Reddy and Kumar, 2019
Integrated Value Model for Sustainable Assessment (MIVES) + Analytic Hierarchy Process (AHP) to calculate the Quantitative Assessment of Life Cycle Sustainability (QUALICS)	Comparison of three remediation options for a contaminated site	Trentin et al. 2019
Multi-Criteria Decision Analysis (MCDA)	Comparison of 50 remediation technologies for a coastal site	Labianca et al., 2020, 2021

	polluted with PAHs, PCBs, and heavy metals	
eDPSIR	Coastal site polluted with PAHs, PCBs, and heavy metals	Labianca et al. 2021
LCA + fuzzy synthetic evaluation (FSE)	A chemical industrial site contaminated by organic chemicals and mercury.	Hu et al., 2022

Furthermore, uncertainty is often associated with the data used to assess sustainability and the relevance or consistency of technical/sustainability criteria are often not entirely unbiased.

Overall, these new tools help to integrate sustainability into soil remediation practices by providing practitioners with a systematic approach to assessing the environmental, social, and economic impacts of different remediation options. By using these tools, practitioners can make more informed decisions that balance sustainability with effectiveness and cost-effectiveness. VSD Avenue, a joint venture of 3 multi-national contractors (the UK, the Dutch, and the Belgian), has worked to recover metals and glass from contaminated soil for processing through their established recycling services. However, this strategy still needs to be expanded and more researched. For example, remediation strategies for metal-contaminated soil are, in general, limited. Most hazardous metal-contaminated soil is deposited in landfill (Hogland et al., 2018), being even mandatory in countries like Denmark (Council of Ministers, 2019). Therefore, it is important to design regulations that support resource recovery and sustainable remediation practices for contaminated soil; incentives for resource recovery can be included, permitting processes should be simplified, and resource recovery options should be considered.

6. Conclusion

Soil contamination has raised many concerns as it affects many critical ecological functions and ecosystem services. This paper explores the emergence of new chemicals from household and industrial activities, their potential as soil contaminants, and the challenges faced in the efforts to remediate them from soil. Although many remediation technologies exist, the need for remediation technologies that provide greatest benefit to the environment and are acceptable to the society informs continued research and the development of new methods and management strategies to sustainably address the problem. The review explores the adoption of a remediation treatment train that encourages resource recovery, enhances circular economy and uses an LCA approach to compare environmental impacts of remediation strategies and explored mechanisms for integrating sustainability into the soil remediation practices Since the SDGs emerged, green remediation strategies have been proposed to remove pollutants, stabilise, or detoxify them, such as soil washing for resource recovery. Many nature-based remediation methods exist, including phytoremediation, microbial oxidation, and reduction, as well as energy-efficient methods such as low temperature thermal desorption and bio-electrokinetic removal. The use of green amendments, such as biochar, can often be the most environmentally friendly strategy, but case-specific sustainability assessments should be considered during the decision-making process. It is also suggested that the combination of several green remediation techniques can improve the overall efficiency of the remediation treatment. With complex sites to be remediated and multi-approach treatments, the integration of the three pillars of sustainability (environmental, economic, and social) is highly recommended within a multi-criteria framework. Overall, resource recovery from contaminated soil has the potential to contribute to sustainable development by reducing waste, conserving natural resources, and promoting social and economic benefits for affected communities. Research and development efforts should focus on improving the efficiency, cost-effectiveness, and environmental performance of these technologies. Resource recovery from contaminated soil should be assessed from a life cycle thinking perspective that considers the environmental, economic, and social impacts of the entire process, from extraction of raw materials to the end of their life cycle. This can help identify opportunities for improvement and ensure that resource recovery strategies are truly sustainable.

To mitigate greenhouse gas emissions, the results of this review are suitable as baseline for future projects in the development of sustainable management practises for the remediation of contaminated soil.

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