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REVIEW

A Review of Life Cycle Assessment of Soil Remediation Technology: Method Applications and Technological Characteristics

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Abstract

With increasing complexity of soil contamination and more variety in remediation technologies, remediation alternatives must be assessed thoroughly and urgently. Life cycle assessment (LCA) can be used to analyze the environmental impact of a technical process and avoid the transfer of the environmental impact. LCA has been applied in soil remediation technology from a single method to a combination of multiple methods, focusing on a few environmental impacts to approximately 20 types of environmental impacts. The life-cycle stage contributions and environmental impact characteristics of LCA are also reviewed. The proposed optimization measures cover the life cycle stages, specific energies or substances, and technology process nodes. The LCA methodology framework of remediation technology must be established by including functional unit determination considering the remediation duration and environmental impact selection methods. Primary, secondary, and tertiary impacts should be considered to reflect technical efficiency, process optimization of technology, and land reuse after restoration. LCA application still needs to be improved in terms of technological processes to reveal the relationship between technical parameters and environmental impacts. This study provides an insightful overview of the methodological elements of LCA in soil remediation technology evaluation, such as the functional unit definition, the system boundary determination, and the selection of impact categories, which can support the revolution of LCA methods applied in soil remediation technology.

Introduction

Over the past few decades, soil contamination has become an increasingly recognized global issue (Food and Agriculture Organization of the United Nations 2021). In Europe, more than 2.5 million contaminated sites have been recognized, of which 14% are expected to require remediation (Hans Bruyninckx 2020). Over 450,000 brownfields (land that is abandoned or underutilized due to pollution from industrial use) are estimated in the US (United States Environmental Protection Agency 2022). Currently, 16.1% of selected soil points in China is contaminated (ministry of environmental protection of the people's republic ofchina 2014). Various physical, chemical, and biological remediation technologies have emerged, with remediation projects soaring from 800 to more than 3600 in China over the period 2017–2021 (Chinese Academy of Environmental Planning 2022), and more than 205,242 cleanups have been completed in the US (United States Environmental Protection Agency 2022). The optimization and comparative selection of these

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technologies must be thoroughly assessed (Huysegoms et al. 2018; Chen et al. 2020).

Life cycle assessment (LCA) has been most popularly used. LCA can analyze the environmental impact of the technical process by considering a variety of categories and avoiding transfer (Onwubuya et al. 2009; Jin et al. 2021). LCA has been applied to soil remediation since 1999. Hitherto, more than 20 technologies have been evaluated and over 10 types of contaminated sites have been remediated. LCA is a useful tool for evaluating and screening remediation technologies and can reduce carbon emissions by 30% via optimization measures (Vocciante et al. 2021). LCA can support decision-making in two ways, including: (1) selecting a remediation technology with better environmental performance by comparing different technologies in terms of energy, resource consumption, and environmental emissions, and (2) providing optimization measures on environmental performance by analyzing the environmental impacts of remediation technology in its life cycle stages (Visentin et al. 2019a; Kalsi et al. 2020).

The use of the technical elements of LCA is the basis for effective assessment and drawing scientific conclusions. Several reviews have been published on this topic (see Table 1). Some challenges of LCA application have been proposed, such as the time factor of functional unit, system boundary determination, neglecting the appropriate quantification of primary impacts associated with the existing contamination of the site and tertiary impacts associated with the post-remediation usage of the land, and failing to include all relevant secondary impacts due to remediation activities (Morais and Delerue-Matos 2010; Owsianiak et al. 2013). They also addressed some aspects that were not or only partly covered, such as the monetary valuation of remediation technology, impact assessment for human health and ecotoxicity, and spatial and temporal differentiation of non-global impact assessments (Morais and Delerue-Matos 2010; Cappuyns 2013a).

However, solving these issues demands systematically analyzing the LCA elements applied in remediation technology. Assessing the environmental sustainability of remediation technologies is challenging because of the details of LCA application (Owsianiak et al. 2013). None of the current studies have individually sorted the elements of the LCA framework to explore how the basic LCA framework and method innovation are applied. How the LCA method be applied to soil remediation technology, how this field be better served, and the characteristics of remediation technologies from the perspective of LCA remain unclear. These issues must be solved by reviewing and summarizing the current literature. Therefore, the objectives of this study are (1) to review existing LCA papers to check how LCA has been implemented in soil remediation technology; (2) to analyze the characteristics of various remediation technologies according to the LCA results, such as life cycle stages and environmental impacts of various technologies, comparison of technologies in different application scenarios, and improvement schemes of technologies for environmental performance; and (3) to reveal the shortcomings of the LCA methodology applied in soil remediation technology and explore solutions to existing issues. This review provides solid support for applying LCA in technology evaluation.

Method

Literature Included

This study was one systematic research, aiming to broaden the knowledge regarding publications related to LCA applied in the remediation technology of contaminated soil. This methodology involved searching scientific databases for peer-reviewed literature related to LCA and soil remediation technologies. Only publications written in English with the full text available were included.

The LCA method included four steps: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation (ISO 2006). The LCA cases in this study involved at least two steps. The framework and procedural components of the LCA were determined according to International Organization for Standardization (ISO) 14040–14043. The literature was divided into two categories to achieve the goals of this study. One is a case study of the life cycle assessment of remediation technologies and the other is a study related to method application and innovation.

Soil Remediation Technology Included

Most of the papers in this review are LCA research on remediation technologies or technology solutions, and a few studies have focused on remediation materials, such as nanomaterials (Martins et al. 2017; Visentin et al. 2019b). The case studies include single-technique analyses, comparative analyses of several techniques, and comparative analyses of technology solutions. Soil remediation technologies can be divided into in situ, ex situ, biological, physical, and chemical remediation according to the location of the contaminated soil or the principle of remediation (Qu et al. 2023a). Soil remediation technologies used in this study are listed in Table 2.

Table 1 The current reviews

Sources	Content	Remediation technology	Conclusions
Morais and Delerue-Matos (2010)	Discuss existing LCA methods and propose models focusing on critical decisions and assumptions of the LCA application	Site remediation activities	LCA has limitations as an adequate holistic decision-making tool since spatial and temporal differentiation of non-global impacts assessment
Lemming, et al. (2010a)	Compare the environmental impacts of different remediation technologies	Soil and groundwater remediation technologies	Earlier studies often used more simplified impact assessment model. The more recent studies based their impact assessment on established methodologies covering the conventional set of impact categories. Ecotoxicity and human toxicity are the impact categories varying the most between these methodologies
Cappuyns (2013a, b)	Engagement of stakeholders and socio-economic consequences of reintroducing a remediated site into the economy	Site remediation technologies	Monetary valuation of remediation methods and the impact assessment for human health and ecotoxicity should be paid more attentions
Owsianiak, et al. (2013)	Methodological problems	Site remediation technologies	Challenges of definition of the functional unit, quantification of primary impacts, quantification of secondary impacts and comparison with no action scenario
Amponsah et al. (2018)	Global warming potential (GWP) from six ex situ soil remediation technologies (ESRTs)	Excavation and disposal, ex situ thermal desorption, ex situ soil vapor extraction, ex situ bioremediation, excavation and incineration, and soil washing	Differences may reflect actual differences in GHG emissions, others may largely be due to assumptions, system boundary, LCA modelling choices, and different LCA approaches, including selected functional units, methods and software, geographic location and processes
Visentin, et al. (2019a, b)	A systematic and bibliographic analysis	Site remediation technologies	Most articles aimed to assess the environmental impacts of remediation techniques. However, several publications also analyzed the economic and social pillars of sustainability by combining LCA with other tools
Caroline and Antônio (2019)	Bibliometric analysis	Nanoparticles in soil remediation	Application of sustainability in its principles, environmental, economic and social, has not yet been carried out in nano remediation
Kalsi et al. (2020)	Discuss the environmental impact of these technologies along with the various emerging trends in the field of microbial remediation in the past decade	Microbial remediation approaches for explosive contaminated soil	ex situ technologies are mainly associated with excavation and replacement, thereby making them energy intensive as well as expensive processes, in situ technologies suffer from the drawbacks of being slow, Integrated treatment technologies seem to be the most promising one

Table 2 Soil remediation technologies involved in the literature

Types		Categories	Description	Key factors for environmental impacts	References
Physical remediation	In situ technologies	In situ thermal desorption (ISTD)	ISTD is a physical remediation method deploying thermal conductive heating of the contaminated soil. It involves the heating of the contaminated clay till by electrically powered heating elements submersed in heater wells	Operational energy demand for electrical heating of the soil, material production	Lemming et al. (2010b)
		Electrokinetic remediation (EK)	Electrokinetic remediation is an in situ soil remediation technique that employs direct current (DC) to mobilize and remove contaminants, such as heavy metals, radionuclides, and organic compounds	Electricity consumption, additives use, and excavation	Kim et al. (2014)
		In situ Multiphase Extraction (MPE)	MPE technology extracts soil vapor, liquids, and groundwater simultaneously. Vacuum extraction increases liquid flow rates and facilitates the volatilization of contaminants. Extracted vapors and liquids are treated on the surface, emitting clean air, CO2, and water	Electricity consumption for system operation	Beames et al. (2015)
		Steam enhanced extraction (SEE)	SEE heats the subsurface by the injection of steam. Solvent vapors continuously extracted, treated with activated carbon filters. Condensed aqueous phase treated separately. Vapor cap prevents rain intrusion, seals surface, reduces heat loss. It requires the installation of a number of wells to generate soil heating as well as extraction wells	On-stie energy consumption and well field material consumption	Lemming et al. (2013)
		Electrical resistance heating (ET-DSP)	ET-DSP places steel electrodes in the wells. Others processes are similar as SEE	Electricity consumption	
		Radio frequency heating	RFH uses specialized antennas, which also may function as extraction wells. Others processes are similar as SEE	Material consumption, such as stainless and fiberglass	
	Ex situ technologies	Excavation and disposal	A small portion of the hazardous soil was first combined with fly ash to stabilize the soil for transportation, followed by deposition in a hazardous landfill. The excavated areas were backfilled with clean backfill from native sources as the remediation progressed	Diesel consumption	Page et al. (1999)
		Excavation and offsite landfilling	The soil is remediated by scraping and deep ploughing, excavation, transporting, and landfilling	Diesel consumption	Inoue and Katayama (2011)
		High temperature thermal desorption	This technique involves the transportation phase of the soil, while the remaining steps are similar to in situ remediation techniques	Diesel and electricity consumption	Blanc et al. (2004); Yasutaka et al. (2016)
		Incineration with natural gas	The soil treatment processes involve excavation and transportation to an incineration site. At the site, the soil is placed in a rotating oven and incinerated at high temperatures along with other organochloride wastes. The resulting gaseous waste underwent a secondary combustion, followed by rapid cooling to prevent the formation of dioxins and furans	Natural gas consumption	Busset et al. (2012)
		Excavation and offsite reuse of contaminated soil for cement	This technique remediates the soil by transportation of the excavated soil to a cement factory	Diesel consumption of soil transportation	Yasutaka et al. (2016)

Table 2 (continued)

Types		Categories	Description	Key factors for environmental impacts	References
Bioremediation	In situ technologies	Bioventing	Bioventing consists of extracting air from the soil in order to create an oxygen inflow to increase contaminant biodegradation. The extracted air is then treated with a biofilter	Material consumption, such as biofilter and bentonite	Cadotte et al. (2007)
		Bioremediation by enhanced reductive dichlorination (ERD)	ERD enhances microbial degradation by injecting a bio-culture of specialized organisms and a fermentable substrate. These organisms follow the anaerobic reductive dechlorination pathway, breaking down trichloroethene (TCE) into sequential compounds: cis-dichloroethene (cis-DCE), vinyl chloride (VC), and ultimately ethene/ethane	Methane consumption	Lemming et al. (2010b)
		On-stie landfarming	On-site landfarming treats contaminated soil directly at the location where it is found. The process typically involves incubation and transport of culture, spreading culture solution, biodegradation, and agitation of soil	Energy demand, such as diesel and electricity Material consumption, such as fertilizer and active carbon	Inoue and Katayama (2011)
		Biofuel cultivation	Biofuel cultivation can promote the microbial degradation of organic contaminants and facilitate soil remediation by increasing organic matter content and enhancing micro-flora	Plant cultivation and transportation of the controller	Suer and Andersson-Skold (2011)
	Ex situ technologies	Excavation and bio-leaching	This technique utilizes microorganisms to extract contaminants from the soil, involving scraping and deep ploughing of the soil, building of bio-leaching cells, aeration, and humidification	Material consumption, such as lime and calcium sulfate	Blanc et al. (2004)
		Excavation and bio-pile treatment	Bio-pile treatment remediates the soil by microbial communities. It improves biodegradation by extracting air, adding nutrients, and enhancing microbial activity to remediate soil	Material consumption, such as biofilter, plastics and gravel	Cadotte et al. (2007)
		Bioremediation with mechanical/electric aeration	Mechanical or electric aeration bioremediation utilizes devices to introduce air or oxygen into polluted soil, enhancing aerobic microorganism activity and promoting pollutant biodegradation	Diesel consumption of transportation and nitrate consumption	Blanc et al. (2004)
		Stimulated biological degradation	It involves enhancing and accelerating the natural process of contaminant biodegradation in soil through the use of techniques and amendments	Organic carbon consumption	Huysegoms et al. (2019a, b)
		Phytoremediation	Phytoremediation uses plants to remove contaminants from soil. It is a sustainable and cost-effective approach that leverages plants' natural abilities to absorb, metabolize, or stabilize pollutants	Diesel consumption in transportation of material and personnel	Vocciante et al. (2019)

Table 2 (continued)

Types	Categories		Description	Key factors for environmental impacts	References
Chemical remediation	In situ technologies	Amendment using coal-based virgin AC	This technique can effectively control the sediment with relatively less cost and ecological disruptions by using AC. It involves the processes of site preparation, AC application, transportation of material and equipment, and monitoring	Coal-based virgin AC consumption	Choi et al. (2016)
	Ex situ technologies	Soil washing process	Soil washing physically separates and removes contaminants from soil through the washing process	Soil excavation and chemical extraction	Oa and Park (2019); Visentin et al. (2019a, b)
		Stabilization/solidification (S/S)	In S/S, a reagent is mixed with contaminated soil to reduce the leachability of contaminants, such as mercury, either through physical binding (solidification) or chemical reactions (stabilization). While S/S does not decrease the total contaminant content, the treated material still needs to be disposed of in a landfill	Stabilization material consumption, such as activated carbon	Hou et al. (2016)

LCA Application in Soil Remediation Technology

Basic Application of LCA Method in Soil Remediation Technology

By sequentially combining the technological elements of LCA, the special challenges identified in different procedures are shown in Fig. 1.

Goal and Scope Definition

Functional Unit of Soil Remediation Technology

Defining functional units is the first step in LCA. Instead of defining the product functional units as unit weight or unit number, the functional units of the technology should consider their purpose. Currently, the total amount of contaminated soil in the site that needs to be remedied or 1 t/m^3 of contaminated soil to be cleaned is generally considered. Moreover, the clean-up level met by removing the contaminated soil was also set. Achieving different remediation levels or pollutant removal rates will result in substantial differences in life-cycle resource inputs and environmental impacts. A typical reference is the case study on the soil Pb remediation at a school (Hou et al. 2017), where the functional unit was defined as “the removal and treatment of Pb contaminated soil to meet the nine cleanup levels used”. Compared to the regulatory guidance value of 255 mg/kg applicable at the time of project implementation, the newly selected optimum clean-up level of 800 mg/kg could increase the net environmental benefit (calculated by subtracting environmental costs from environmental benefits) by 3% (Hou et al. 2017). Another problem with functional units is that the treatment duration is not covered (Lemming et al. 2010b). Generally, LCA studies of products do not consider duration factors. However, for remediation technology, different remediation times and efficiencies lead to obvious differences in environmental impacts, as is elaborated in “Methods Combined with the Characteristics of Soil Remediation Technology” Sect.

System Boundary of Soil Remediation Technology

In a narrow sense, the system boundary of remediation technology ranges from cradle to grave, including raw material and energy acquisition, equipment acquisition and usage, transportation, construction, technology implementation, and waste disposal. In addition to focusing on the technology implementation itself, the energy consumption of excavators and other equipment used on-site, transport of

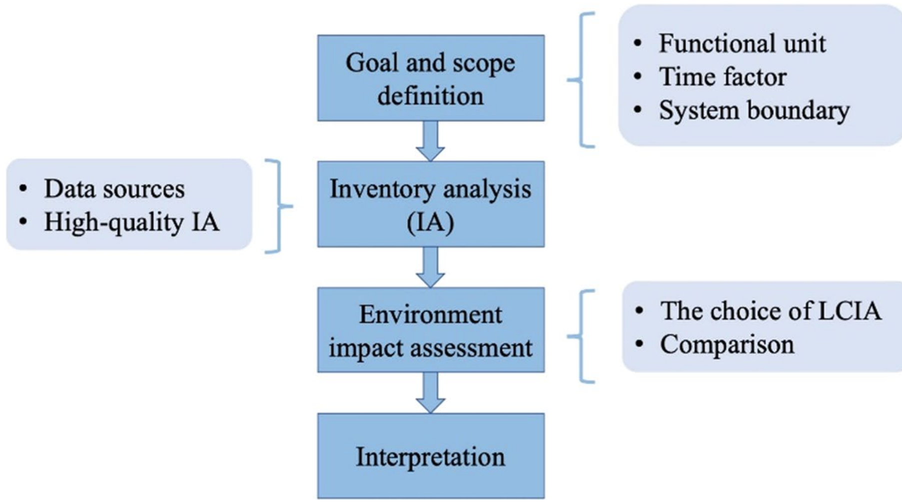

Fig. 1 LCA framework and challenges

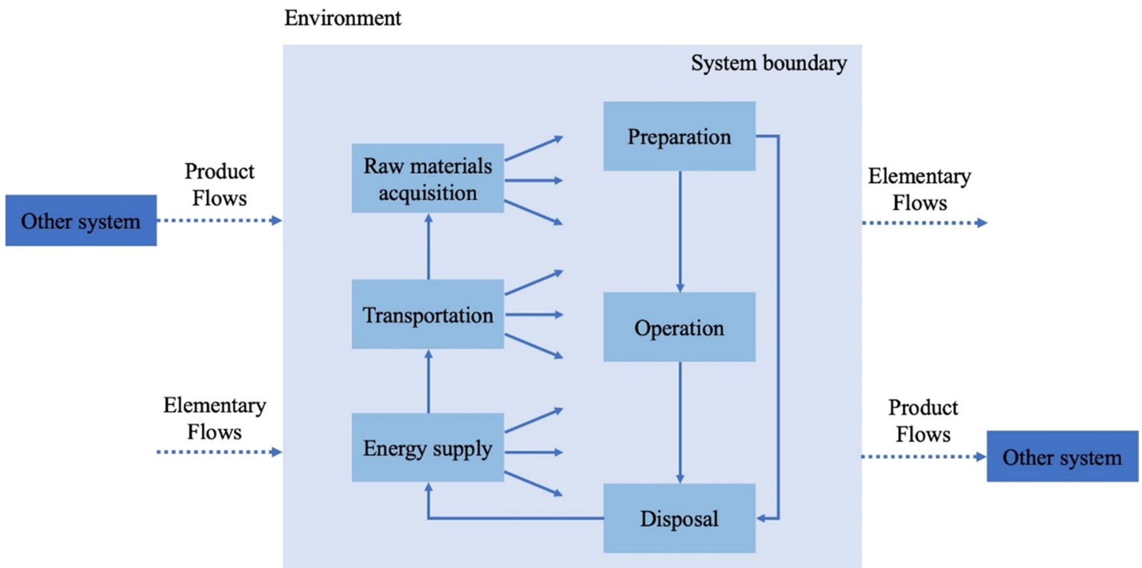

Fig. 2 System boundary of soil remediation technology

soil and equipment from and to the site, passenger transport from and to the site, and the energy demand of remediation installation were considered (Cappuyns 2013a). However, parts of the life cycle stages are neglected because complex processes and data are unavailable. All life cycle stages are recommended to be considered to avoid environmental impacts transferred. Transportation, for example, is a part of all remediation technologies that is sometimes overlooked, but contributes up to 90% toward the impact (Choi et al. 2016).

Broadly, the system boundary of remediation technology can be summarized as preparation, operation, and disposal (Fig. 2). All remediation activities related to the three stages, like raw materials acquisition, transportation, and energy supply, should be covered. Preparation stage involves works before the technology implementation, such as concrete layer removal and movable shed construction in site preparation (Beames et al. 2015), screening and blending processes of infrared high temperature incineration technology and the crusher and pug mill processes of base catalyzed decomposition technology (Hu et al. 2011). Operation, the core stage of soil remediation, involves all works during the technology implementation, such as thermal treatment processes of remediation technologies based on thermophysics (Jin et al. 2021), cultivation in phytoremediation (Vocciante et al. 2019), and soil aeration in bioremediation (Busset et al. 2012). Disposal refers to works after the technology implementation, involving disposal of contaminated biomass harvested (Vocciante et al. 2019), offsite landfill disposal (Yasutaka et al. 2016), and removal of sheet pile wall and asphalting in ex situ remediation (Lemming et al. 2010b), etc.

A typology was proposed in which the primary impacts are associated with changes in the environmental quality of a site. Secondary impacts refer to the environmental impacts of the life-cycle stages during the technology implementation. Tertiary impacts include the environmental impacts due to the subsequent development and occupation of the remediated site and the affected life cycles of other sites. Primary impacts are difficult to be assessed using LCA because they are strictly site-specific and not functionally determined. Secondary impacts have always been evaluated using an LCA. Tertiary impacts are both important and negative. Regarding reductions in primary impacts associated with rehabilitation, tertiary impacts may help offset and possibly annul secondary impacts (Lesage et al. 2007b; Hou et al. 2014). Hitherto, only fibe studies have included all three types of impacts (Owsianiak et al. 2013).

Life Cycle Inventory Analysis

Life Cycle Inventory

In this step, a large amount of data was collected and processed. Some studies provided raw data or life cycle inventory (LCI). The data sources were site-specific. Some of these were from laboratory experiments, project reports, published scientific papers, and industrial consultants. For background data, a public LCA database, such as Ecoinvent, was the main source.

However, some data sources are unclear and their quality is uncertain. A list of data is recommended to be provided by category, such as input and output, energy consumption, material consumption, primary impact data, secondary impact data, and tertiary impact data. Data sources and quality analysis should be provided as required by the ISO. This ensures the transparency of the data and traceability and reliability of the results.

Inventory Analysis

A good LCA case study can be conducted if a high-quality inventory analysis is available. An advantage of inventory analysis is its ability to perform specific analysis of the substance of concern. Some of the studies in this review only carried out inventory analysis, focusing on certain energy sources, such as coal, oil, and natural gas, or emissions, such as CO_2, SO_2, and NO_X. A LCI analysis was carried out to compare in situ stabilization/solidification and disposal in landfills and they focused on several key emissions and concluded that cement production accounts for the largest proportions of CO_2 (91%), N_2O (88%), NO_X (90%), and SO_2 (93%) (Harbottle et al. 2007).

Life Cycle Impact Assessment

In the cases within the scope of this study, the life cycle impact assessment (LCIA) methods used include EDIP, ReCiPe, and Indicator 99, among which the most commonly used method is ReCiPe. Different LCIA methods correspond to different types of environmental impacts (Table 3). The choice of impact categories is subjective, so no consensus has been made on the impact categories to assess (Morais and Delerue-Matos 2010). However, choosing an appropriate environmental impact based on the characteristics of soil pollution and remediation processes has not been thoroughly explored by current research.

Environmental impacts should be chosen according to the characteristics of remediation technology, goal of the study, regional impacts, and life cycle stages. Currently, global warming potential (GWP) is the focus of research on general environmental impact. Not all technologies need to evaluate greenhouse gas (GHG) emissions, and rules for selecting environmental impacts need to be established according to their characteristics. For example, if thermal remediation is evaluated, more attention should be paid to the environmental impacts of resources and energy consumption (Hou et al. 2018). If the tertiary impacts of remediation technology are discussed, resource utilization and land use should be focused. The environmental impact characteristics of remediation technology are elaborated in "Environmental Impacts Characteristics" Sect.

Life Cycle Interpretation

Life cycle interpretation covers the following elements (ISO 2006): (i) identification of significant issues according to the results of LCI and LCIA, (ii) evaluation, including consistency check, completeness check, and sensitivity check, and (iii) conclusions, limitations, and recommendations. LCA practices on soil remediation technology focus on the identification of significant issues, sensitivity check, and conclusions. In general, contribution analysis is implemented to identify hotspots, that is, life cycle stages whose contribution to the impact category is greater than the even distribution of that impact across the life cycle stages (Laurent et al. 2020). For LCA research on soil remediation, the contribution of three types of impacts (namely, primary, secondary, and tertiary impact) to the total life cycle environmental impacts can also be analyzed (Hou et al. 2018; Jin et al. 2021). A sensitivity check is usually accomplished to assess and enhance the robustness of LCA results. One-at-a-time approach and scenario analysis are most frequently

Table 3 Environmental impact categories used in soil remediation technologies

Sources	Categories	Sources	Categories
Page et al. (1999)	GWP, SWB, multimedia contaminant fate and toxicity, land use assessment, and Residual human toxicity burden	Choi et al. (2016)	GHG, ozone depletion, eutrophication potential, acidification potential, summer and winter smog, heavy metal emissions, and carcinogen emissions
Blanc et al. (2004)	Resource flux: natural gas, crude coal, crude lignite Emission flux: CO_2, CH_4, NO_X, SO_X, Cd, Pb	Lim et al. (2016)	Greenhouse gas (GHG) emissions, water consumption, total energy usage, and air pollutants (SO_X, NOx, and PM10)
Toffoletto et al. (2005)	**Global impact**: climate change, ozone depletion, acidification, eutrophication and photochemical smog **Local impact**: ecotoxicity water acute, ecotoxicity water chronic, ecotoxicity soil chronic, human toxicity air, human toxicity water, human toxicity soil and bulk waste	Yasutaka et al. (2016)	**Endpoint:** human health, social assets, biodiversity, primary production **Midpoint:** global warming, acidification, urban air pollution, photochemical oxidant, ecotoxicity, human toxicity, eutrophication, resource consumption, waste
Cadotte et al. (2007)	**Midpoint (TRACI)**: Biogenic CO_2, Fossil CO_2, BOD205, Calcium **Endpoint (Impact 2002 +)**	Favara and Gamlin (2017)	**TRACI:** GWP, Smog, Eutrophication, Respiratory Effects **ReCiPe:** Fossil Fuel Depletion, Water Depletion, Agricultural Land
Harbottle et al. (2007)	Global warming, ozone depletion, acidification, eutrophication, photochemical smog, ecotoxicology, human health cancer effects (HHC), human health non cancer effects (HHNC) and human health criteria	Inoue and Katayama (2011), Vocciante et al. (2016, 2019)	GWP
Suer and Andersson-Skold (2011)	**Endpoint (ReCiPe 2008)**: human health, ecosystem and resources **Midpoint (EPD)**: GWP, ozone layer depletion, photochemical oxidation, acidification, eutrophication and gross caloric values	Lemming et al. (2010b, 2013)	**EDIP 2003:** non-toxic impacts (global warming, acidification, eutrophication, and ozone formation) **USEtox™:** toxic impacts (human toxicity cancer, human toxicity noncancer, Respiratory inorganics and ecotoxicity)
Hu et al. (2011)	**Endpoint (IMPACT 2002 +)**: Human Health, Ecosystem Quality, Climate Change, Resources **Midpoint (IMPACT 2002 +)**: Non-renewable energy, Carcinogens and non-carcinogens, Global warming, Terrestrial ecotoxicity, Respiratory inorganics	Pranjic et al. (2018)	**Endpoint:** ecosystem, human health, and resources **Midpoint:** climate change human health, ozone depletion, human toxicity, photochemical oxidant formation, ionising radiation, climate change ecosystem, terrestrial ecotoxicity, terrestrial acidification, freshwater eutrophication, freshwater ecotoxicity, agricultural land occupation, natural land transformation, metal depletion, fossil depletion
Busset et al. (2012)	Human toxicity, terrestrial ecotoxicity, photochemical oxidation (low NOx), ionizing radiation, freshwater sedimentary ecotoxicity, freshwater aquatic ecotoxicity, marine sedimentary ecotoxicity, marine aquatic ecotoxicity, ozone layer depletion (Steady state), global warming, eutrophication, acidification and abiotic depletion	Huysegoms et al. (2019a, b)	Climate change human health, ozone depletion, human toxicity, photochemical oxidant formation, ionising radiation, climate change ecosystem, terrestrial ecotoxicity, terrestrial acidification, freshwater eutrophication, freshwater ecotoxicity, agricultural land occupation, natural land transformation, metal depletion, fossil depletion
Cappuyns (2013a, b)	Soil loss, groundwater loss, energy use, air emission, surface water emission, waste formation, space use	Chen et al. (2020)	CO_2, SO_2, NO_X and PM, COD, and NH_3N
Kim et al. (2013, 2014)	Greenhouse gas (GHG) emissions, energy consumption, water consumption, PM10, NO_X, and SO_X	Oa and Park (2019)	**Midpoint:** the quantities of energy, CO_2, SO_X, and NO_X **Endpoint:** monetary value

Table 3 (continued)

Sources	Categories	Sources	Categories
Beames et al. (2015)	Climate change human health, ozone depletion, human toxicity, photochemical oxidant formation, ionising radiation, climate change ecosystem, terrestrial ecotoxicity, terrestrial acidification, freshwater eutrophication, freshwater ecotoxicity, agricultural land occupation, natural land transformation, metal depletion, fossil depletion, land resource	Hou et al. (2014, 2016)	**Endpoint**: ecosystem, human health, and resources **Midpoint**: climate change human health, ozone depletion, human toxicity, photochemical oxidant formation, ionising radiation, climate change ecosystem, terrestrial ecotoxicity, terrestrial acidification, freshwater acidification, freshwater eutrophication, freshwater ecotoxicity, agricultural land occupation, natural land transformation, metal depletion, fossil depletion

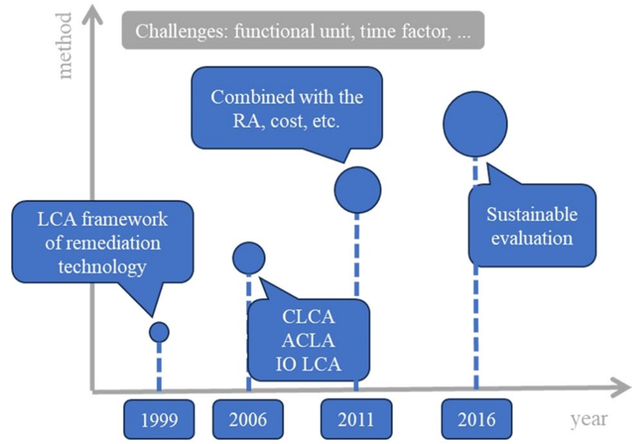

Fig. 3 The revolution of method application

adopted to reveal the influence of specific parameters (e.g., transportation distance, electricity production, and effective time of stabilization reagent) on LCA results in the field of soil remediation (Lemming et al. 2010a, b; Jin et al. 2021; Martins et al. 2017). After significant issues and sensitive factors have been identified, conclusive results can be drawn. Simultaneously, limitations and recommendations of the LCA results should be provided to avoid misleading the policy-making of soil remediation. At present, consistency and completeness checks have been determined as key steps in the interpretation (Laurent et al. 2020) but are still overlooked in LCA practices of soil remediation, which will reduce the reliability of LCA results.

Innovation Application of LCA

Since the establishment of the LCA framework for remediation technology in 1999 (Diamond et al. 1999), scholars have conducted innovative research on LCA methods to better apply LCA method to this field. It mainly focuses on two aspects: (1) the application of hybrid LCA, Attributional LCA (ALCA), Consequential LCA (CLCA), and other types of LCA methods, and (2) the combination of LCA with other methods (Fig. 3).

LCA Framework of Remediation Technology

In 1999, a simple LCA framework for soil remediation technology was created, considering elements of the functional unit and system boundary. In the follow-up studies, a trend was observed toward establishing an LCA framework according to the specific characteristics of the remediation site. However, no unified framework was developed for defining the application of LCA in the field of remediation technology.

A life cycle framework (LCF) was developed, including a qualitative life cycle management approach (LCM) and an adapting LCA. The LCA of a remediation technology should include appropriate life cycle stages, a long-term time horizon, a spatial boundary encompassing the contaminated site, and other affected locations, a process boundary, and an impact assessment method that considers site- and process-related metrics. Importantly, remediation activities must consider the temporal boundary and the functional unit should be related to the equivalent amount of treated soil (Diamond et al. 1999; Page et al. 1999). Another LCA framework suggests that the functional unit is an ensemble of activities aimed at achieving a certain risk level after remediation (Volkwein et al. 1999). These studies are the first to explore LCA application with important elements such as the setting of functional unit and system boundary.

An integrated LCA is required to make the LCA framework more suitable for specific contaminated site. For example, in a technology of building an LCA conceptual framework for oil spill remediation, six steps were included and the environmental, human health, and socioeconomic impacts were covered (Ugwuoke and Oduoza 2019).

Methods Covering Primary, Secondary, and Tertiary Impacts

Over half of the existing LCA studies did not include primary impacts and nearly all LCA studies systematically excluded tertiary impacts. These three types of impacts reflect the environmental impacts of soil pollution status, remediation technology implementation, and land use of post-remediation (Lesage et al. 2007a). To cover all three types of impacts, some researchers have explored the methodologies.

An LCA model, including all three types of impacts, was presented based on CLCA rather than the more common ALCA. ALCA assesses the burdens of the life cycle and its subsystems, whereas CLCA aims to describe the technosphere-wide effects of changes within the life cycle (van Zanten et al. 2018; Bamber et al. 2020). ALCA is commonly used to evaluate secondary impacts. The scope of a CLCA is far more complex than that of an ALCA, which includes reoccupying land after restoration and the effects of other site uses. For example, the tertiary impacts of brownfield rehabilitation depend on the type, context, and location of other sites affected by rehabilitation. The study included vacant urban sites and suburban green fields (Lesage et al. 2007c). In addition, the hybrid LCA method was used to evaluate tertiary impacts. Because the tertiary impact is related to the land use after restoration, the input–output LCA (IO-LCA) can better evaluate the tertiary impact under social and economic operation. In the cases of the sediment contamination at London Olympic Park, waterway transport was dredged. Regarding the tertiary impact, the main beneficial use of the waterways was barge transport, which may avoid 3.5 million tonnes of transport for local construction work (Hou et al. 2014a).

Methods for More Accurate Evaluation Results

The difference between process LCA (PLCA) and IO-LCA has always been a popular topic in LCA research. One of the differences is that IO-LCA can reduce truncation error (Beylot et al. 2020). These errors were mainly attributed to three components that were overlooked in the PLCA of remediation technology: consulting and project management services, mobilization/demobilization, and temporary usage of capital equipment (Hou et al. 2014).

The hybrid LCA offers a more complete system boundary than PLCA. A case study at the London Olympic Park site found that the hybrid method could correct a significant truncation error in PLCA: 32% of the secondary impact in soil washing and 8% in landfilling. The hybrid LCA method corrected these truncation errors by incorporating readily available project cost data, offering an economical tool for solving this problem in traditional LCA (Hou et al. 2014).

Methods Combined with the Characteristics of Soil Remediation Technology

Balance of Eliminating Risk and Generation

The characteristics of the soil pollution and remediation technologies should be considered when constructing an LCA research. Soil remediation technology differs from other products because it eliminates pollution, while creating pollution during the implementation process. Traditionally, remediation practitioners have used risk assessment (RA) as an important decision-making tool for choosing cleanup levels. Therefore, some studies combined RA with LCA (Hou et al. 2017; Huysegoms et al. 2019a, b). Elaborate analysis of contaminated soil is a component of RA. The standardized RA procedure identifies threshold contaminant concentrations for adverse effects on ecosystems and human health and examines the fate and transport of these contaminants along source-to-receptor pathways. The LCA results are typically used to select and compare the “greenest” technology for a given remedial objective. However, LCA has not been used to select the “greenest” cleanup level.

A framework combination of RA and LCA was proposed to identify the optimum cleanup level (Hou et al. 2017). Based on the possible clean-up level, the exposure risk and health benefits were calculated using RA, and the environmental impacts were calculated using LCA. After completing these two parallel lines of tasks, the results were combined using an appropriate weighting strategy. This combination provides a net environmental benefit (NEB) for each clean-up level. Overall, the study confirmed that an optimum cleanup level exists when considering both environmental benefits and costs, and that the appropriate cleanup level can be quantitatively determined by calculating the NEBs (Hou et al. 2017).

Other risk factors combined with LCA from the perspective of residual risk were also introduced. Based on the trade-off between risk reduction and increase in cost, energy consumption, and CO_2, the ranking of technologies was determined using RA and economic input–output LCA (EIO-LCA). The expanded evaluation index, the rescue number for soil with life cycle costing (LCC) and EIO-LCA, comprises two scales: risk–cost, risk–energy consumption, or risk–CO_2 emission of remediation (Inoue and Katayama 2011). This study solved the monotony of environmental impact by combining residual risk with remediation cost and environmental impact, and the characteristics of technology were more intuitively.

Time Efficiency

When LCA is applied to products, the time factor is seldom considered, but soil remediation technology is substantially affected (Toffoletto et al. 2005). Hitherto, the LCA of remediation technologies presents large variations over time. The monitoring of natural attenuation, biopile treatment, and soil bioventing were estimated to take 300, four, and eight years, respectively. Biopile treatment has a greater environmental impact than any other treatment (Cadotte et al. 2007). Integrating the time factor, namely technical efficiency, into the LCA is challenging.

A land-use impact method based on ReCiPe was used to link the time factors and environmental impacts. Land occupation runs over all life cycles and includes the duration of occupation. By comparing the two cases, ex situ treatment of soil produces larger impacts in all energy-related impact categories than in situ multiphase extraction, but has a lower land resource because of the shorter remediation time (Beames et al. 2015).

Standard LCA methods do not consider land use as a finite and increasingly scarce resource. Instead, land use was accounted for in terms of ecosystem damage and biodiversity loss (Beames et al. 2015). Valuing land use throughout its lifecycle remains a challenge. However, land use currently solves the time-to-repair problem, allows time to be considered in functional units, and can show differences in environmental impact.

Methods for More Comprehensive Evaluation

LCA can give more information about environmental impact, such as the categories listed in Table 3. However, LCA does not consider the social and economic aspects; therefore, a broader approach is necessary. Typically, decision-makers or technology selectors pay more attention to the economic aspect; therefore, many studies use LCC, monetize LCA, and social and economic assessment method. By 2016, scholars begun to pay more attention to the sustainable evaluation based on LCA, covering various factors such as environment, economy, and society (Huang et al. 2016).

LCC can be used to estimate total cost prospectively based on all remediation processes. The LCC estimates the total cost with higher accuracy than that based on the mean unit cost, reflecting the site-specific characteristics of remediation. Inoue and Katayama (2011) estimated the total cost of three types of technology using LCC. Disposal had the highest total cost, followed by biopiles, land farming, and high temperature thermal desorption (HTTD).

In addition, environmental impact results of LCA can be monetized using different techniques (Huysegoms et al. 2018; Oa and Park 2019). Huysegoms et al. (2018) used the monetization method: Stepwise 2006 and Ecovalue 08 for excavation and off-site cleaning. When expressing the environmental impact in monetary terms, the mid-point environmental impact is aggregated by applying economic weighting factors to express a monetary value. The results were then compared using social cost–benefit analysis (CBA). In such a social CBA, all impacts on society are included, and the net present value (NPV) is calculated for a case study or policy scenario that includes direct and indirect financial costs and benefits, health and environmental benefits, and other relevant impacts.

In this field, sustainability assessment has attracted increasing attention in recent years and is used to evaluate the performance of remediation technology in three or more dimensions: the environment, economy, and society. Such studies generally establish sustainability criteria or indicators in which LCA is used to evaluate environmental impacts (Harbottle et al. 2007; Song et al. 2018; O'Connor et al. 2019; Li et al. 2022).

In conclusions, the integration of LCA with other tools, such as social CBA and LCC, enables a comprehensive assessment of soil remediation technologies across multiple dimensions such as technical, environmental, economic, and social aspects. The results obtained from these methods can be compared individually or integrated into a single value through weighting, enabling support for technological decision-making (Zanghelini et al. 2018). This provides more comprehensive and informed recommendations for decision-making in soil remediation technologies, which is crucial for the sustainable development of the soil remediation industry. Therefore, further exploration and application of LCA should be undertaken in future research.

Assessment Software for Remediation Technology

The major software packages, like SimaPro and GaBi, have been emphasized and some other software packages, like Open LCA and Umberto, were also used. These software tools can help conduct the LCA model and link it to the database. Different software tools provide varying values, but it can be modeled and compared using unified software tools.

Many researchers and institutions have established assessment software platforms based on LCA as technology evaluation and selection tools (Yasutaka et al. 2016). The evaluation platform mentioned within the scope of this study are listed in Table 4. Some green sustainability assessment tools do not integrate the LCA method but also evaluate environmental factors, such as energy and pollutant emissions.

Volkwein et al. (1999) first introduced software for technical evaluation in 1999, when an LCA calculation model of soil remediation technology was established. The LCI lists 40 datasets including nine types of environmental impacts. Not only is this preliminary application of LCA in the field of soil remediation technology, but it is also a typical LCA evaluation tool that can be used for other technologies. Subsequently, some tools integrate other stakeholder concerns such as economic and social factors.

Further development and improvement of LCA software is recommended, considering not only the new development of soil remediation technology but also the availability of data, easy interpretation, and usefulness of the outcome of the calculations. Another problem with existing impact assessment models is that different countries require different evaluation models and basic databases, owing to different country-based LCA data.

Data quality is important for LCA. The elementary data in software should be transparent and traceable. The temporal representativeness, geographical representativeness, technological representativeness, completeness, and reliability of the data should be clarified (Cooper and Kahn 2012).

Characteristics of Remediation Technologies Based on LCA

Evolution of Remediation Technology Evaluated

Current research mainly focuses on evaluating a single technology, comparing two or more technologies, and technical solutions. Few studies have focused on a single type of soil pollution, such as mercury or polychlorinated biphenyls (Hu et al. 2011). However, actual soil pollution is often compound, requiring a combination or coupling of multiple remediation technologies. A single remediation technology does not result in thorough remediation (Huysegoms et al. 2019a, b). Since 2018, technology combinations closer to restoration projects have been evaluated. For example, IO-LCA was conducted on technology combinations and the advantages and disadvantages of different technology combination options were analyzed (Chen et al. 2020).

Characteristics of Life Cycle Stages

The life cycle stages should be clearly defined, and the main soil remediation activities should be included. It can not only avoid the omission and duplication of technical repair activities and prevent the transfer of environmental emissions, but also analyze the contribution of each life cycle stage to determine the potential for energy conservation and emission reduction.

The life cycle of remediation technologies typically consists of three main stages: raw material and energy acquisition, site processing, and post-site processing. Substages may exist in any life cycle, including waste management, monitoring, and transportation (Page et al. 1999). The principles used to determine the life cycle are similar, whereas the energy consumption activities and emissions involved in life cycle stages are substantially different due to the obvious differences in the remedial process of different technologies. This article summarizes the specific life-cycle stages of different types of remediation technologies, as is shown in Tables 5 and 6. Based on this, the life cycle characteristics of different soil remediation technologies were analyzed.

In Situ Remediation Technology

Bioremediation Technology

Bioremediation technologies are mainly applicable to organic, petroleum, and heavy metal pollution. Table 5 presents the four major in situ bioremediation technologies: bioventing, enhanced reductive dechlorination, land farming, and phytoremediation. The life cycle stages of these technologies are primarily determined based on the actual processes. For instance, the life cycle stages of enhanced reductive dichlorination considered as a microbial remediation include monitoring well installation, pumping and injection of bio culture, monitoring, and transportation of materials, equipment, and personnel (Lemming et al. 2010b). Phytoremediation technology follows different life cycle stages, including site preparation, system operation, and disposal (Vocciante et al. 2019). Planting and related activities, including the cultivation and disposal of plants, are the main elements in system operation and disposal phase and are the largest contributors to environmental impact.

Table 4 Evaluation software

Year	Name	Country	LCA	Contents	Characteristics
1999	Baden-Wurttemberg	Germany	Yes	14 kinds of environmental impacts	54 Unit processes among 13 decontamination technologies, ten ensuring technologies, and 31 secondary technologies (construction, transports, air purification, water treatment)
2009	Remediation strategy for soil and groundwater pollution (RemS)	Denmark	Yes	Remediation efficiency, secondary impacts, environmental impacts, remediation cost, and remediation period	It includes thirteen different remediation technologies
2009	PIRTU	Finland	–	Risk, environmental impacts, cost, and the others (Psychosocial, cultural, and ecological impacts)	The factors are evaluated using the weighting technique
2009	Green remediation evaluation matrix (GREM)	US	–	Environmental impacts	It is a qualitative evaluation tool in a checklist format
2009	Sustainable remediation tool (SRT)	US	–	Used energy, generated greenhouse gas, and cost	It includes eight different remedial schemes
2011	SitewiseTM	US	–	Water, energy, and greenhouse gas	/
2013	BATNEEC (Best Available Technology Not Entailing Excessive Costs)	Flanders	Yes	Environmental, technical and financial criteria	The environmental criteria include: the achievement of legal objectives, the decrease of contamination load, the restrictions for use after remediation, the use of secondary resources, direct emissions to other environmental compartments, other adverse environmental effects during remediation (not specified) and the duration of the remediation versus objectives
2016	Green remediation assessment tool for Japan (GRATJ)	Japan	Yes	Environmental impacts are assessed and integrated using LIME2	Processes of 14 remediation methods for heavy metal contamination and 12 for volatile organic compound contamination are built into the tool. This tool can evaluate 130 inventory inputs/outputs and integrate those inputs/outputs into 9 impact categories, 4 integrated endpoints, and 1 index
2016	Spreadsheet-based evaluation tool (SEFA)	Taiwan	Yes	Energy, air, water resources, materials and wastes, and land and ecosystem	–
2019		South Korea	Yes	Energy, CO_2, SO_X, and NO_X	An Excel-based program containing seven soil remediation alternatives. Qualitative and quantitative evaluation

Table 5 Life cycle stages of in situ soil remediation technologies

Category	Duration	Reference	Technologies	Contaminants	Life cycle stages
Bio	8.27 years	Cadotte, et al. (2007)	Bioventing	Diesel-contaminated site	Site preparation, treatment, site dismantling
	38 years	Lemming, et al. (2010b)	Enhanced reductive dechlorination	Trichloroethene-contaminated site	Monitoring wells installation, pumping and injection of molasses and bio culture, monitoring, transportation
	60 months	Inoue and Katayama (2011)	On site landfarming	Dieldrin contaminated an agricultural field	Incubation, transport of culture, spreading culture solution, biodegradation, agitation of soil, monitoring
	–	Suer and Andersson-Skold (2011)	Biofuel cultivation	Mineral oil	Salix viminalis cultivation, transportation, groundwater monitoring well production
	2 years	Vocciante et al. (2019)	Crop cultivation	Arsenic and lead	Site preparation, system operation (cultivation and related activities), disposal of contaminated biomass harvested
Physical	3 months	Lemming, et al. (2010b)	in situ thermal desorption	Trichloroethene-contaminated site	Heater and extraction wells installation, heating of soil, ventilation of soil and pumping of water, activated carbon treatment, monitoring of soil, transportation (materials, equipment, people)
	12 months	Kim, et al. (2014)	Electrokinetic remediation	Multi metal-contaminated site	Remedial investigations; remedial action construction; remedial action operation, and long-term monitoring
	–	Pranjic, et al. (2018)	Capping	The old zinc-works	Removal of overgrowth, screening and crushing, geotechnical composite production, placing of the composite at the excavation site, spreading of the top layer-covering material, leaching emissions from geotechnical composite
	–	Lemming et al. (2013)	Electrical resistance/radio frequency heating	Pce (perchloroethylene)	Electrode/ RFH antenna and extraction wells and power distribution production, transportation (materials and personnel), system operation
Chemical	30 years	Choi et al. (2016)	in situ amendment using coal-based virgin AC	Sediment contaminated with hydrophobic organic contaminants	Site preparation, AC application, transportation (material and equipment), monitoring

Table 6 Life cycle stages of ex situ soil remediation technologies

Category	References	Technology	Contaminants	Life cycle stages
Bio	Blanc et al. (2004)	Excavation and bio-leaching	Sulfur	Scraping and deep ploughing of the soil, building of bio-leaching cells, aeration, humidification, processing of acid streams, disposal of treatment waste, dewatering, disposal to landfill by truck, putting the soil back into place, disposal of geotextiles
	Cadotte et al. (2007)	Excavation and biopiles treatment	Diesel	Site preparation, excavation, soil heaping, treatment, backfilling, site dismantling, asphalt recycling (process-based)
	Busset et al. (2012)	Bioremediation with mechanical aeration	Polychlorobiphenyl	Excavation, soil transportation, soil installation in anaerobic conditions, soil aeration, disassembly, landfill
	Lim et al. (2016)	Landfarming process	Petroleum	Site preparation, installation, system operation, and system dismantling/waste disposal
Physical	Page et al. (1999)	Excavation and disposal	Lead	Raw materials acquisition, site processing, waste management, transportation
	Inoue and Katayama (2011)	High temperature thermal desorption	Dieldrin	Temporary enclosure, excavation, dust reduction, drainage treatment, monitoring, backfilling and recovery of soil function, transport of soil, thermal desorption
	Choi et al. (2016)	Dredge-and-fill	Hydrophobic organic contaminants	Site preparation (dewatering), transportation (sediment), mechanical dredging, backfill, disposal, monitoring
	Yasutaka et al. (2016)	Excavation and offsite reuse of contaminated soil for cement	Arsenic-contaminated	Site preparation, soil retention structure, excavation, refilling, monitoring
	Pranjic et al. (2018)	Incineration	The old zinc-works	Excavation, hazardous waste incineration, metal recovery from bottom ash, disposal of incineration residues, refill
	Chen et al. (2020)	ex situ thermal desorption	VOCS, SVOCS, mercury	Soil excavation and transportation, wastewater treatment, ex situ thermal desorption
Chemical	Hou et al. (2016)	Stabilization/solidification	Mercury	Excavation/backfill, stabilization, landfilling
	Oa and Park (2019)	Soil washing	TPH	Information on contaminated soil, earthwork and transportation, facility installation, selection of solvents, soil remediation, demolition

In general, bioremediation can be summarized into three stages: site preparation (monitoring well production and installation, transportation, and plant cultivation), site processing (remediation activities like monitoring and bio culture injection), and site disposal (biomass disposal and dismantling of monitoring wells). Notably, in situ bioremediation usually lasts for a long time and environmental impacts of personnel, equipment, sample transportation, and monitoring are not negligible (Cadotte et al. 2007; Lemming et al. 2010b).

Chemical Remediation Technology

Chemical remediation technology has been widely applied in soil remediation due to its high efficiency and cost-effectiveness (Song et al. 2022; Qu et al. 2023b). However, very limited information exists in the literature for environmental impact assessment of chemical remediation technologies. The work by Choi et al. (2016) is the only study on in situ chemical remediation technology available in the literature (Table 5). The life cycle stages of in situ chemical remediation technology for activated carbon amendment include site preparation, activated carbon application, transportation of material and equipment, and monitoring (Choi et al. 2016). For chemical remediation, the amendment or oxidizing reagent production stages are important to the whole life. For instance, nano-remediation methods have gained substantial attention due to their exceptional features, like sensitivity and enhanced catalytic features, and have been documented in many cleanup sites (Fei et al. 2022). However, the production stage of nanomaterials used in remediation always causes undesirable impacts on human health and the environment (Martins et al. 2017; Visentin et al. 2019a). Therefore, more efforts should be focused on the material production stage to identify significant issues in the LCA of chemical remediation technologies.

Physical Remediation Technology

In situ physical remediation technologies are more widely used, and LCA research is more widely used than bioremediation and chemical remediation. Different remedial approaches, such as heat treatment, electrokinetic remediation, and on-site containment, have been considered. In the heat treatment method, the life cycle stages mainly include heating and extraction system production (such as heater, extraction well), transportation, and heat treatment stage. In contrast to heat treatment, electrokinetic remediation technology has stricter constraints in practical applications where sampling inspection and pretreatment of the site are required. Therefore, remedial investigations and remedial action construction are generally included in the life cycle stages of the electrokinetic remediation technology (Kim et al. 2014; Vocciante et al. 2016). Containment, capping and disposal methods occupy the mainstream position in contaminated site risk management measures because of their operability and other advantages. The life cycle stages of the capping method mainly include site preparation, transportation of materials, mechanical backfill, and monitoring (Table 5).

Considering environmental impacts, heat treatment and electrokinetic consume substantial electricity and steam, and are thereby major contributors to environmental impacts (Lemming et al. 2013). In the capping approach listed in this article, the transportation stage contributes the most to the majority of the environmental impacts. However, the proportion of the total environmental impacts mainly depends on the transportation distance between the site and capping material supply place.

Ex Situ Remediation Technologies

Referring to Table 6, characteristics of life cycle stages on ex situ remediation technologies are analyzed. Compared to in situ remediation technology, soil excavation is an essential life-cycle stage of ex situ remediation technology.

Bioremediation Technology

LCA research on ex situ bioremediation technologies involve phytoremediation, land-farming methods, biopiles, and bioleaching (Table 6).

The life cycle stages of different ex situ microbial remediation approaches can be divided into four stages: site preparation, soil treatment, backfilling, and waste management. Site preparation includes unit processes of soil excavation and transportation, and installation of facilities used in soil remediation, such as the installation of aeration systems, site walls, and monitoring systems. The soil remediation stage mainly involves actual remediation processes of different remedial means and other related activities, such as piles construction and plants cultivation. The contribution of environmental impacts is quite different for ex situ bioremediation technologies because different specific activities are considered in the remedial process.

Chemical Remediation Technology

The LCA practices of ex situ chemical remediation technologies mainly focus on soil washing and solidification/stabilization (Table 6). The life cycle stages of these two types of remediation technologies are different. Soil washing can be described as soil excavation, transportation, soil washing, and wastewater treatment. Some studies considered the installation and dismantling of devices (Oa and Park 2019). Owing to the short processing time, monitoring was not included in the scope of the life cycle phase. Among all life cycle stages, the soil washing stage had the most significant environmental impacts. Excavation/backfill, stabilization, and landfilling are the major stages of solidification/stabilization technology. As described in "In Situ Remediation Technology" Sect., the production process of the materials required for solidification also has the greatest contribution on the overall environment impacts (Hou et al. 2016).

Physical Remediation Technology

Excavation and disposal and heat treatment are the commonly used ex situ remediation. Heat treatment methods include incineration, ex situ thermal desorption, and co-processing in cement kiln.

The life cycle is considered to have four stages when applying LCA to asses excavation and disposal: contaminated soil excavation, transportation, off-site landfill disposal, and clean soil backfilling. In addition, site wall installation and demolition, soil dewatering, and dust removal can be included in the life cycle as pretreatment and waste management stages. Generally, transportation consumes a large quantity of fuel, making it the highest contributor to all environmental impacts. However, when specific impact categories are considered, the contributions of other stages may be the most important. For example, the waste disposal stage and site wall material consumption contributed the most when the solid waste burden and toxic-type impacts were considered.

In contrast to in situ thermal remediation, soil excavation, transportation, and backfilling are important life cycle phases in ex situ heat-based remedial approaches. Furthermore, incineration methods include the disposal of incineration residues. The stage influence on the total impacts is similar to that of the in situ thermal treatment approach; that is, the soil remediation process contributes the most.

Environmental Impacts Characteristics

Chosen Environmental Impacts Categories

The LCIA methods can be divided into two types: mid-point type and end-point type (Table 3). In the same LCIA methods, midpoint impacts can be transformed into endpoint impacts by revealing the damage pathways between them (Huijbregts et al. 2017) (Fig. 4). The mid-point method is typically used to evaluate the environmental burden of a single technology (Kim et al. 2013; Lim et al. 2016). When performing technical comparisons, the endpoint method, which evaluates the environmental burden using a single score, can display the comparison results more intuitively (Cadotte et al. 2007; Suer and Andersson-Sköld 2011; Jin et al. 2021).

Different LCIA methods have different calculation models and proportions for environmental impacts categories. Similar to increasing the number of environmental types, the end point method requires more data and calculations and has typical regional characteristics. When combined methods were used to evaluate the same technology, the uncertainty of the results is larger compared with that of an independent method.

Regarding the selection of environmental impact categories, GHG emissions have become one of the most important research hotspots in environmental science; thus, they are mandatory environmental impacts in LCA research. Other global environmental or non-toxic impacts, such as ozone depletion, acidification, eutrophication, and photochemical smog, are also focal points in soil remediation LCA studies (Harbottle et al. 2007; Suer and Andersson-Sköld 2011) (Table 3).

Considering regional-scale impacts, researchers have frequently focused on the toxic effects of remediation activities on local water, humans, and soil. More attention should be paid to such environmental impacts when comprehensively evaluating whether soil remediation can reduce overall environmental load. Scholars will determine some specific environmental types, such as solid waste formation, Cd and Pb accumulation, to analyze the key environmental impacts (Blanc et al. 2004; Cappuyns 2013b).

Categories of environmental impacts have gradually developed from focusing on a few specific types to more impact categories (Lemming et al. 2010a). Recently, the number of environmental impacts has exceeded 10, covering a wider range and facilitating a comprehensive analysis of the environmental contributions of different remediation technologies.

Environmental Impacts of Different Remediation Technology

Due to the different LCIA methods chosen in these cases, summarizing the environmental impact characteristics of each remediation technology is difficult. Generally, a comparison of the environmental impacts of different technologies is used; for example, bioremediation with mechanical aeration, bioremediation with electric aeration, and incineration; bioremediation with mechanical aeration has a larger GWP and incineration has a larger ozone layer depletion (Cappuyns 2013b). When the environmental impacts are standardized or an endpoint approach is used, the environmental impacts can be compared. Excavations and biopiles have the greatest ecotoxicity, followed by eutrophication. Soil washing, landfilling, thermal desorption, and soil stabilization/solidification have a greater impact on human health than resources and ecosystems (Kim et al. 2014; Oa and Park 2019).

The key issue is that there are no specific categories of environmental impacts for different remediation technologies. Environmental impacts should reflect material/energy requirements, emissions, type of soil pollution, and the purpose of restoration. The methods for selecting environmental impact categories require further research.

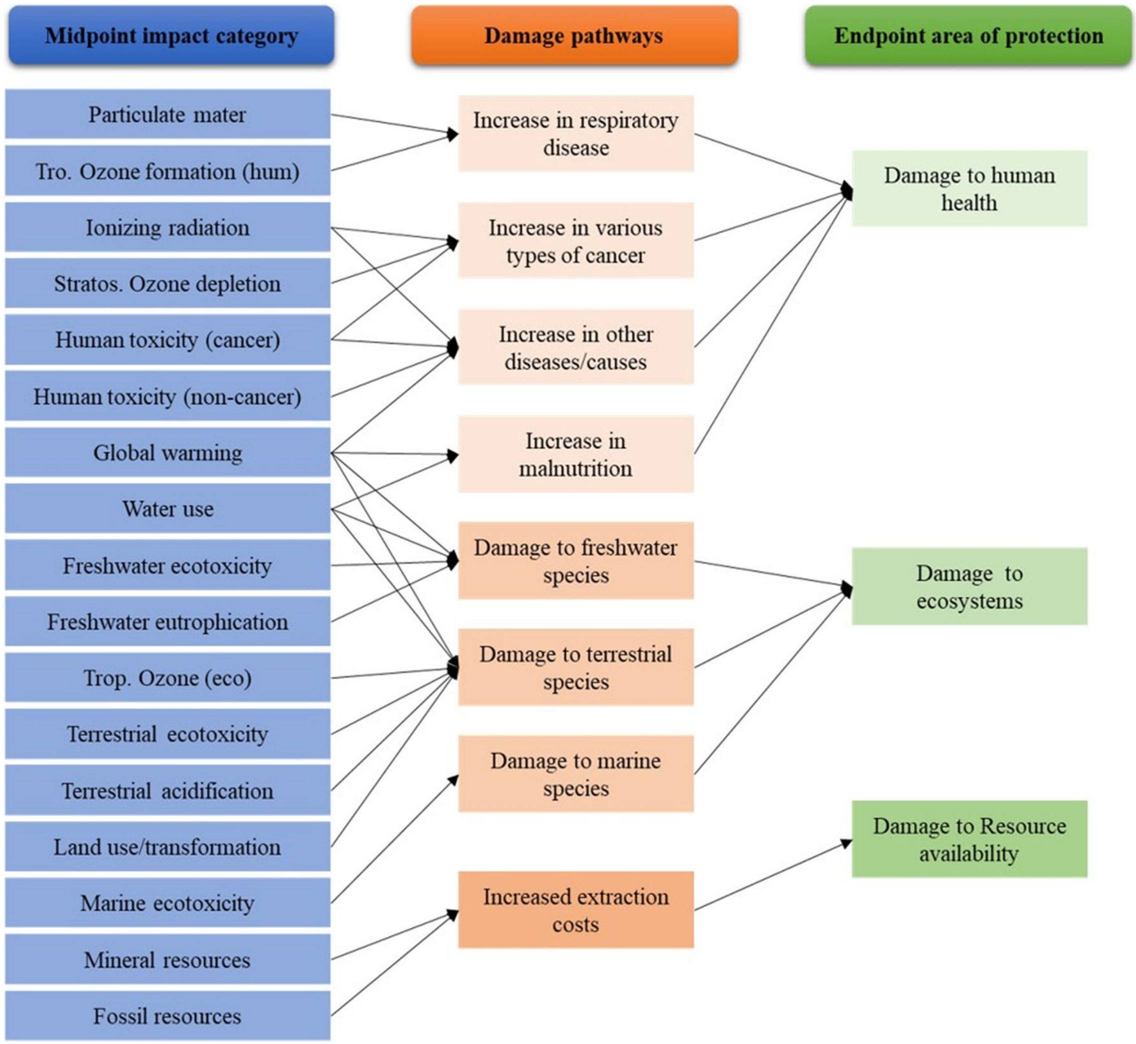

Fig. 4 Overview of the midpoint and endpoint impacts covered in ReCiPe 2016

Improvement Options for Remediation Technologies

The environmental impact based on LCA is difficult to interpret on its own, but can be useful for comparing remediation alternatives. However, the most important implication is that users can deduce the most relevant factors that cause the highest environmental impact and take specific measures to decrease the environmental impact. Identifying the life cycle stages, energy sources, raw materials, processes, and environmental impact categories of technologies with high environmental impacts to make recommendations for environmental impact mitigation is the object of this LCA study. Currently, the technical improvements proposed in LCA include the following:

Improvement Options Related to Life Cycle Stages

A full LCA can identify specific life cycle stages of technology that contribute the most to the environmental impact. Different technologies have different environmental characteristics during their life cycle. For example, in the ex situ bioremediation of diesel-contaminated soil, 49.6% of the total impact is generated by site preparation (enclosure and shelter installation, biopile containment, asphalt paving, and clay spreading). Many studies of life cycle stage of transportation indicate the importance of this stage. For dredge-and-fill and capping options, transportation was the largest contributor to secondary impacts for most environmental categories. Transportation accounted for approximately 60% and 90% of the total GHG emissions from dredge-and-fill and capping processes, respectively (Choi et al. 2016). Transportation is also a major contributor to S/S alternatives, primarily attributed to off-haul landfills (Hou et al. 2016).

Improvement Options Related To Energy and Material Use

The LCA traces the materials and energy used in the process and identifies the energy and materials that contribute the most to the environmental impact, including the materials used in infrastructure, such as cement and steel, and the auxiliary materials used in technology implementation. For example, cement production is a notable contributor to stabilization and solidification alternatives. Coal-based powdered activated carbon was the largest contributor to the stabilization/solidification of coal. For both types of thermal desorption, electricity was the most important contributor to the overall impact: 54% for acid-facilitated low-temperature desorption and 72% for high-temperature desorption. The use of green cement is recommended to reduce electricity consumption and utilize renewable energy sources (Hu et al. 2011; Hou et al. 2016).

Improvement Options Related to Technique Process

An important purpose of LCA is to analyze the technological process and provide suggestions for technical improvement and green design. Some studies have put forward suggestions for technology optimization, but overall, the technical processes must be analyzed further. For example, for steam-enhanced extraction, four improvement options have been proposed: the use of a condensing steam boiler, concrete sandwich vapor cap, bio-based activated carbon, and fiberglass injection wells. Each of the four identified improvement options contributed almost equally to reducing the environmental impact, whereas the use of a condensing boiler had the highest improvement potential (50%) for reducing resource depletion.

Improvement Options Related to Environmental Impacts

The LCIA method can normalize different environmental impact categories, compare the relative values of different environmental impacts, and identify the largest environmental impact or pollutant emissions. Many studies use ReCiPe to calculate the environmental impact and finally summarize human health, ecosystems, and resources into impact points to compare the magnitude of these three kinds of mid-point environmental impacts. For example, S/S-coal and S/S-biochar have a greater impact on human health than the other two types of biochar (Hou et al. 2016).

Comparative Analysis

LCA results of remediation technology are sensitive to site-specific conditions. Directly transferring the LCA results from one case study at one site to another is difficult, and therefore, the most environmentally friendly technology cannot be specified conclusively.

Comparison of Different Technologies in the Same Contaminated Site

Most LCA studies have focused on specific contamination sites. For the same contaminated site under the same functional units and boundary systems, LCA can provide an effective analysis and support for technology comparison and selection. For example, by comparing soil washing with landfilling at sediment-contaminated sites, soil washing was found to be superior to landfilling in terms of environmental impact (Hou et al. 2014). Thermal desorption has a better GHG emission performance than S/S for mercury-contaminated sites (Hou et al. 2016). According to both evaluation methods, biofuel remediation followed by traditional excavation-and-refill remediation caused less damage to the environment (Suer and Andersson-Sköld 2011).

Comparison of the Same Technology in Different Contaminated Sites

Same Technology Used in Sites with the Same Pollution But Different Volumes When the same technology is applied to the same polluted site but with different pollution capacities, the environmental impact does not increase with the capacity. LCA research involves the use of equipment and energy efficiency among other issues. The results showed that when the treated soil volume at a large site was almost 10 times larger than that at a small site, the environmental impacts and resource consumption were only approximately five times larger (Lemming et al. 2013). Thus, the results indicate that in situ thermal remediation is more environmentally efficient at larger sites which is not only because of a relatively larger heat loss for the small site compared to the large site, but also because of a relatively greater number of installations placed more closely together at a smaller site (Lemming et al. 2013).

Comparison of Same Technology in Different Types of Pollution Sites Comparing the impact of the same technology applied to different contaminated sites is difficult, even if the implementation process is consistent. Taking the soil washing used for sediment pollution and Pb contamination as an example, the LCA method (hybrid LCA and PLCA), LCIA method (ReCiPe and energy consumption), and system boundaries were all varied (Kim et al. 2013; Hou et al.

2014). The differences were significant when they were compared. For in situ thermal desorption (ISTD), conventional high-temperature desorption was estimated to produce 357 kg CO_2-eq. of GHG emissions. In two other studies, 150 and 180 kg CO_2-eq. were determined (Hou et al. 2016). Variability in LCA studies is due to different reasons. These can be attributed to a variety of reasons, such as the geographical and technological scope of modelling, functional unit and comparability, assumptions made on upstream impact, energy consumption, the LCA database, and software used. When the aforementioned conditions are the same, the type of contaminated site that the technology is suitable for remediation can be identified by comparing LCA results.

Conclusions and Recommendations

Conclusions

The status characteristics of the LCA methodology applied in soil remediation technology are revealed by reviewing the existing literature. The review showed that most case studies are conducted on the specific polluted site for evaluating individual technology or comparing multiple technologies. The unit process that contributes significantly and the environmental hotspots can also be identified according to the quantity results of environmental impacts on soil remediation technologies. However, the LCA methodology is usually adjusted to adapt the evaluation of the specific soil remediation technology, causing the LCA results considerably different. Therefore, to promote the standardized implementation of the LCA methodology to better comparable conclusions, a unified LCA framework of soil remediation technology considering the following technical issues should be established:

(1) The functional unit must consider quantity and quality, that is, the amount, cleanup level, and duration time of contaminated soil to be cleaned. The time factor, measured by land occupation and transformation, can distinguish the efficiencies of different technologies.
(2) The system boundary can be determined according to the life cycle of the soil remediation technologies, that is, the preparation, operation, and disposal stages. And all remediation activities related to these three stages should be covered as possible.
(3) The selection of impact categories necessarily considers the types of soil pollution and the typical characteristics of the technology because different pollutants and technologies can lead to distinct environmental applications. The primary, secondary, and tertiary impacts are suggested to be covered to reveal the technology's efficiency, identify the optimization opportunities of the technology itself, and provide guidance for land use after restoration, respectively. Simultaneously, regional factors, like geographical zone and the industrial sector, should be considered to reveal the regional or global environmental impacts.
(4) Life cycle interpretation should cover the following elements: identification of significant issues, evaluation, and conclusions, limitations, and recommendations. The environmental hotspots of soil remediation technologies, like the contribution of primary, secondary, and tertiary impacts to the total environmental impacts, should be clearly identified. A sensitivity check should also be implemented to enhance the reliability of LCA results.

Recommendations

LCA has a few limitations such that it cannot fully consider the characteristics of soil remediation, such as risk assessment and land-use issues. Therefore, a combination of LCA and other methods could more comprehensively evaluate soil remediation technologies. (1) Multi-dimensional evaluation. The sustainability assessment of soil remediation technologies is one of the main development directions. To provide more holistic decision support, LCA should be combined with other methods, such as cost–benefit analysis and multi-criteria decision analysis, to make trade-offs in multiple dimensions or indicators (like cost efficiency, environmental friendliness, and energy efficiency) and assess the comprehensive performance of remediation technology. (2) More innovative methods. Soil plays an important role in ecosystem service. Considering the characteristics of polluted soil, types of pollutants, and environmental pollution mechanisms, the integration of LCA and ecosystem service evaluation can simultaneously help reveal the influence of remediation activities on the environment and ecosystem services.

To better support the technology optimization and selection, LCA should be applied thoroughly during the technology implementation process to explore the mechanism that technical parameters influence environmental impacts. For example, exploration on the variation of environmental impacts caused by the variation of the thermal desorption temperature can help optimize the environmental performance of the specific process. Simultaneously, the existing evaluation tools are also recommended to be further developed and improved, which should not only consider the newest development in soil remediation technologies but also the operability of the tool itself in data availability, interpretability, and usefulness of the evaluated results. It will aid the evaluation and screening of technology solutions for actual soil remediation projects. Moreover, LCA studies are recommended to be more transparent in disclosing the assumptions, methods, and system boundaries, which will definitely improve the quality of the life cycle inventory, results comparability, and confidence of LCA practitioners.

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Declarations

Conflict of interest The authors declare that they have no potential conflict of interest with respect to the research, authorship or publication of this article.

References

Amponsah NY, Wang JY, Zhao L (2018) A review of life cycle greenhouse gas (GHG) emissions of commonly used ex situ soil treatment technologies. J Clean Prod 186:514–525. https://doi.org/10.1016/j.jclepro.2018.03.164

Bamber N, Turner I, Arulnathan V et al (2020) Comparing sources and analysis of uncertainty in consequential and attributional life cycle assessment: review of current practice and recommendations. Int J Life Cycle Assess 25:168–180. https://doi.org/10.1007/s11367-019-01663-1

Beames A, Broekx S, Heijungs R et al (2015) Accounting for land-use efficiency and temporal variations between brownfield remediation alternatives in life-cycle assessment. J Clean Prod 101:109–117. https://doi.org/10.1016/j.jclepro.2015.03.073

Beylot A, Corrado S, Sala S (2020) Environmental impacts of European trade: interpreting results of process-based LCA and environmentally extended input–output analysis towards hotspot identification. Int J Life Cycle Assess 25:2432–2450. https://doi.org/10.1007/s11367-019-01649-z

Blanc A, Métivier-Pignon H, Gourdon R, Rousseaux P (2004) Life cycle assessment as a tool for controlling the development of technical activities: application to the remediation of a site contaminated by sulfur. Adv Environ Res 8:613–627. https://doi.org/10.1016/S1093-0191(03)00034-0

Bruyninckx, H (2020) Soil contamination widespread in Europe. https://www.eea.europa.eu/highlights/soil-contamination-widespread-in-europe#:~:text=Theremaybeasmanyas2.5million,identifiedandaround15%25havebeenremediated

Busset G, Sangely M, Montrejaud-Vignoles M et al (2012) Life cycle assessment of polychlorinated biphenyl contaminated soil remediation processes. Int J Life Cycle Assess 17:325–336. https://doi.org/10.1007/s11367-011-0366-7

Cadotte M, Deschênes L, Samson R (2007) Selection of a remediation scenario for a diesel-contaminated site using LCA. Int J Life Cycle Assess 12:239–251. https://doi.org/10.1065/lca2007.05.328

Cappuyns V (2013a) LCA based evaluation of site remediation opportunities and limitations. Chim Oggi - Chem Today 31:18–21

Cappuyns V (2013b) Environmental impacts of soil remediation activities: quantitative and qualitative tools applied on three case studies. J Clean Prod 52:145–154. https://doi.org/10.1016/j.jclepro.2013.03.023

Caroline V, Antonio T (2019) Sustainability in life cycle analysis of nanomaterials applied in soil remediation. Environ Sci Eng. https://doi.org/10.1007/978-981-13-2227-3_66

Chen C, Zhang X, Chen J et al (2020) Assessment of site contaminated soil remediation based on an input output life cycle assessment. J Clean Prod 263:121422. https://doi.org/10.1016/j.jclepro.2020.121422

Chinese Academy of Environmental Planning (2022) 2021 Market analysis report of soil environmental remediation industry. https://www.caep.org.cn/sy/gczxzx/zxdt/202201/t20220119_967506.shtml

Choi Y, Thompson JM, Lin D et al (2016) Secondary environmental impacts of remedial alternatives for sediment contaminated with hydrophobic organic contaminants. J Hazard Mater 304:352–359. https://doi.org/10.1016/j.jhazmat.2015.09.069

Cooper JS, Kahn E (2012) Commentary on issues in data quality analysis in life cycle assessment. Int J Life Cycle Assess 17:499–503. https://doi.org/10.1007/s11367-011-0371-x

Diamond ML, Page CA, Campbell M et al (1999) Life-cycle framework for assessment of site remediation options: method and generic survey. Environ Toxicol Chem 18:788–800. https://doi.org/10.1002/etc.5620180427

Favara P, Gamlin J (2017) Utilization of waste materials, non-refined materials, and renewable energy in in situ remediation and their sustainability benefits. J Environ Manage 204:730–737. https://doi.org/10.1016/j.jenvman.2017.03.097

Fei L, Bilal M, Qamar SA et al (2022) Nano-remediation technologies for the sustainable mitigation of persistent organic pollutants. Environ Res 211:113060. https://doi.org/10.1016/j.envres.2022.113060

Food and Agriculture Organization of the United Nations (2021) Global assessment of soil pollution: report. https://www.fao.org/3/cb4894en/online/cb4894en.html

Harbottle MJ, Al-Tabbaa A, Evans CW (2007) A comparison of the technical sustainability of in situ stabilisation/solidification with disposal to landfill. J Hazard Mater 141:430–440. https://doi.org/10.1016/j.jhazmat.2006.05.084

Hou D, Al-Tabbaa A, Guthrie P et al (2014) Using a hybrid LCA method to evaluate the sustainability of sediment remediation at the London Olympic Park. J Clean Prod 83:87–95. https://doi.org/10.1016/j.jclepro.2014.07.062

Hou D, Gu Q, Ma F, O'Connell S (2016) Life cycle assessment comparison of thermal desorption and stabilization/solidification of mercury contaminated soil on agricultural land. J Clean Prod 139:949–956. https://doi.org/10.1016/j.jclepro.2016.08.108

Hou D, Qi S, Zhao B et al (2017) Incorporating life cycle assessment with health risk assessment to select the "greenest" cleanup level for Pb contaminated soil. J Clean Prod 162:1157–1168. https://doi.org/10.1016/j.jclepro.2017.06.135

Hou D, Song Y, Zhang J et al (2018) Climate change mitigation potential of contaminated land redevelopment: a city-level assessment method. J Clean Prod 171:1396–1406. https://doi.org/10.1016/j.jclepro.2017.10.071

Hu XT, Zhu JX, Ding Q (2011) Environmental life-cycle comparisons of two polychlorinated biphenyl remediation technologies: Incineration and base catalyzed decomposition. J Hazard Mater 191:258–268. https://doi.org/10.1016/j.jhazmat.2011.04.073

Huang WY, Hung W, Vu CT et al (2016) Green and sustainable remediation (GSR) evaluation: framework, standards, and tool: a case study in Taiwan. Environ Sci Pollut Res 23:21712–21725. https://doi.org/10.1007/s11356-016-7305-x

Huijbregts MAJ, Steinmann ZJN, Elshout PMF et al (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22:138–147. https://doi.org/10.1007/s11367-016-1246-y

Huysegoms L, Rousseau S, Cappuyns V (2018) Friends or foes? Monetized life cycle assessment and cost-benefit analysis of the site remediation of a former gas plant. Sci Total Environ 619–620:258–271. https://doi.org/10.1016/j.scitotenv.2017.10.330

Huysegoms L, Rousseau S, Cappuyns V (2019) Chemical or natural? Including LCA in social CBA to compare remediation alternatives for a dry-cleaning facility. Sustainability 11:1–16. https://doi.org/10.3390/su11071975

Inoue Y, Katayama A (2011) Two-scale evaluation of remediation technologies for a contaminated site by applying economic input-output life cycle assessment: risk-cost, risk-energy consumption and risk-CO_2 emission. J Hazard Mater 192:1234–1242. https://doi.org/10.1016/j.jhazmat.2011.06.029

ISO (2006) ISO 14044: environmental management life cycle assessment requirements and guidelines. Environ Manag 3:54

Jin Y, Wang L, Song Y et al (2021) Integrated life cycle assessment for sustainable remediation of contaminated agricultural soil in China. Environ Sci Technol 55:12032–12042. https://doi.org/10.1021/acs.est.1c02535

Kalsi A, Celin SM, Bhanot P et al (2020) Microbial remediation approaches for explosive contaminated soil: critical assessment of available technologies, recent innovations and future prospects. Environ Technol Innov 18:100721. https://doi.org/10.1016/j.eti.2020.100721

Kim DH, Hwang BR, Moon DH et al (2013) Environmental assessment on a soil washing process of a Pb-contaminated shooting range site: a case study. Environ Sci Pollut Res 20:8417–8424. https://doi.org/10.1007/s11356-013-1599-8

Kim DH, Yoo JC, Hwang BR et al (2014) Environmental assessment on electrokinetic remediation of multimetal-contaminated site: a case study. Environ Sci Pollut Res 21:6751–6758. https://doi.org/10.1007/s11356-014-2597-1

Laurent A, Weidema BP, Bare J et al (2020) Methodological review and detailed guidance for the life cycle interpretation phase. J Ind Ecol 24:986–1003. https://doi.org/10.1111/jiec.13012

Lemming G, Hauschild MZ, Bjerg PL (2010a) Life cycle assessment of soil and groundwater remediation technologies: literature review. Int J Life Cycle Assess 15:115–127. https://doi.org/10.1007/s11367-009-0129-x

Lemming G, Hauschild MZ, Chambon J et al (2010b) Environmental impacts of remediation of a trichloroethene-contaminated site: life cycle assessment of remediation alternatives. Environ Sci Technol 44:9163–9169. https://doi.org/10.1021/es102007s

Lemming G, Nielsen SG, Weber K et al (2013) Optimizing the environmental performance of in situ thermal remediation technologies using life cycle assessment. Groundw Monit Remediat 33:38–51. https://doi.org/10.1111/gwmr.12014

Lesage P, Deschênes L, Samson R (2007a) Evaluating holistic environmental consequences of brownfield management options using consequential life cycle assessment for different perspectives. Environ Manage 40:323–337. https://doi.org/10.1007/s00267-005-0328-6

Lesage P, Ekvall T, Deschênes L, Samson R (2007b) Environmental assessment of brownfield rehabilitation using two different life cycle inventory models part 1: methodological approach. Int J Life Cycle Assess 12:391–398. https://doi.org/10.1065/lca2006.10.279.1

Lesage P, Ekvall T, Deschênes L, Samson R (2007c) Environmental assessment of Brownfield rehabilitation using two different life cycle inventory models. part 2: case study. Int J Life Cycle Assess 12:497–513. https://doi.org/10.1065/lca2006.10.279.2

Li S, He L, Zhang B et al (2022) A comprehensive evaluation method for soil remediation technology selection: case study of ex situ thermal desorption. Int J Environ Res Public Health. https://doi.org/10.3390/ijerph19063304

Lim H, Kwon IS, Lee H, Park JW (2016) Environmental impact assessment using a GSR tool for a landfarming case in South Korea. Environ Monit Assess 188:1–9. https://doi.org/10.1007/s10661-016-5243-1

Martins F, Machado S, Albergaria T, Delerue-Matos C (2017) LCA applied to nano scale zero valent iron synthesis. Int J Life Cycle Assess 22:707–714. https://doi.org/10.1007/s11367-016-1258-7

Ministry of environmental protection of the people's republic of China (2014) The ministry of environmental protection and the ministry of land and resources issued a bulletin on the national soil pollution survey. http://www.mep.gov.cn/gkml/hbb/qt/201404/t20140417_270670.htm

Morais SA, Delerue-Matos C (2010) A perspective on LCA application in site remediation services: critical review of challenges. J Hazard Mater 175:12–22. https://doi.org/10.1016/j.jhazmat.2009.10.041

O'Connor D, Zheng X, Hou D et al (2019) Phytoremediation: climate change resilience and sustainability assessment at a coastal brownfield redevelopment. Environ Int. https://doi.org/10.1016/j.envint.2019.104945

Oa S, Park JW (2019) An environmental impact assessment model with monetary valuation for remediation in South Korea. KSCE J Civ Eng 23:4168–4173. https://doi.org/10.1007/s12205-019-1737-z

Onwubuya K, Cundy A, Puschenreiter M et al (2009) Developing decision support tools for the selection of "gentle" remediation approaches. Sci Total Environ 407:6132–6142. https://doi.org/10.1016/j.scitotenv.2009.08.017

Owsianiak M, Lemming G, Hauschild MZ, Bjerg PL (2013) Assessing environmental sustainability of remediation technologies in a life cycle perspective is not so easy. Environ Sci Technol 47:1182–1183. https://doi.org/10.1021/es305279t

Page CA, Diamond ML, Campbell M, McKenna S (1999) Life-cycle framework for assessment of site remediation options: case study. Environ Toxicol Chem 18:801–810. https://doi.org/10.1002/etc.5620180428

Pranjic AM, Oprckal P, Mladenovic A et al (2018) Comparative life cycle assessment of possible methods for the treatment of contaminated soil at an environmentally degraded site. J Environ Manage 218:497–508. https://doi.org/10.1016/j.jenvman.2018.04.051

Qu J, Li Z, Wu Z et al (2023a) Cyclodextrin-functionalized magnetic alginate microspheres for synchronous removal of lead and bisphenol a from contaminated soil. Chem Eng J 461:142079. https://doi.org/10.1016/j.cej.2023.142079

Qu J, Liu R, Bi X (2023b) Remediation of atrazine contaminated soil by microwave activated persulfate system: Performance, mechanism and DFT calculation. J Clean Prod 399:136546. https://doi.org/10.1016/j.jclepro.2023.136546

Song Y, Hou D, Zhang J et al (2018) Environmental and socio-economic sustainability appraisal of contaminated land remediation strategies: a case study at a mega-site in China. Sci Total Environ 610–611:391–401. https://doi.org/10.1016/j.scitotenv.2017.08.016

Song P, Xu D, Yue J et al (2022) Recent advances in soil remediation technology for heavy metal contaminated sites: a critical review. Sci Total Environ 838:156417. https://doi.org/10.1016/j.scitotenv.2022.156417

Suer P, Andersson-Sköld Y (2011) Biofuel or excavation? Life cycle assessment (LCA) of soil remediation options. Biomass Bioenerg 35:969–981. https://doi.org/10.1016/j.biombioe.2010.11.022

Toffoletto L, Deschênes L, Samson R (2005) LCA of ex situ bioremediation of diesel-contaminated soil. Int J Life Cycle Assess 10:406–416. https://doi.org/10.1065/lca2004.09.180.12

Ugwuoke OS, Oduoza CF (2019) Framework for assessment of oil spill site remediation options in developing countries a life cycle perspective. Procedia Manuf 38:272–281. https://doi.org/10.1016/j.promfg.2020.01.036

United States Environmental Protection Agency (2022) Overview of EPA's brownfields program, US EPA. https://www.epa.gov/brownfields/overview-epas-brownfields-program

Van Zanten HHE, Bikker P, Meerburg BG, de Boer IJM (2018) Attributional versus consequential life cycle assessment and feed optimization: alternative protein sources in pig diets. Int J Life Cycle Assess 23:1–11. https://doi.org/10.1007/s11367-017-1299-6

Visentin C, da Silva Trentin AW, Braun AB, Thomé A (2019a) Application of life cycle assessment as a tool for evaluating the sustainability of contaminated sites remediation: a systematic and bibliographic analysis. Sci Total Environ 672:893–905. https://doi.org/10.1016/j.scitotenv.2019.04.034

Visentin C, da Silva Trentin AW, Beatriz Braun A, Thomé A (2019b) Lifecycle assessment of environmental and economic impacts of nano-iron synthesis process for application in contaminated site remediation. J Clean Prod 231:307–319. https://doi.org/10.1016/j.jclepro.2019.05.236

Vocciante M, Caretta A, Bua L et al (2016) Enhancements in electro kinetic remediation technology: environmental assessment in comparison with other configurations and consolidated solutions. Chem Eng J 289:123–134. https://doi.org/10.1016/j.cej.2015.12.065

Vocciante M, Caretta A, Bua L et al (2019) Enhancements in phytoremediation technology: Environmental assessment including different options of biomass disposal and comparison with a consolidated approach. J Environ Manage 237:560–568. https://doi.org/10.1016/j.jenvman.2019.02.104

Vocciante M, de Folly DA, Franchi E et al (2021) CO2 footprint analysis of consolidated and innovative technologies in remediation activities. J Clean Prod 297:126723. https://doi.org/10.1016/j.jclepro.2021.126723

Volkwein S, Hurtig HW, Klöpffer W (1999) Life cycle assessment of contaminated sites remediation. Int J Life Cycle Assess 4:263–274. https://doi.org/10.1007/BF02979178

Yasutaka T, Zhang H, Murayama K et al (2016) Development of a green remediation tool in Japan. Sci Total Environ 563–564:813–821. https://doi.org/10.1016/j.scitotenv.2016.01.018

Zanghelini GM, Cherubini E, Soares SR (2018) How multi-criteria decision analysis (MCDA) is aiding life cycle assessment (LCA) in results interpretation. J Clean Prod 172:609–622. https://doi.org/10.1016/j.jclepro.2017.10.230