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Low input remediation techniques for contaminated site management

Paul Bardos, *[a] Jinyu Lai,[b] Lisa Pizzol,[c] Antonio Sellitri,[c] Nazaré Couto,[d] Virginie Derycke,[e] Dominique Guyonnet,[e] Timothy M. Vogel,[f] Jurate Kumpiene[g] and Andrew Cundy[h]

Risk-based land management emphasises remediation to manage risks from land contamination, aiming to reduce human and environmental risks while enabling site reuse and redevelopment. Since the mid-2000s, sustainable remediation has gained prominence, driven by global sustainability agendas such as the United Nations 2030 Agenda and the European Green Deal. These frameworks encourage integrated approaches that maximise remediation benefits and minimise negative impacts. Low-input remediation techniques (LIRT) represent a family of approaches characterised by lower energy and resource demands, often leveraging natural processes, renewable resources, or energy sources. Examples include methods using biochar, photosynthesis, or renewable energy systems. LIRT overlap with concepts like gentle remediation options (GRO) and nature-based solutions (NBS), which employ natural processes to address contamination while delivering environmental and societal benefits. While LIRT are typically effective for pathway management rather than source control, they offer sustainable outcomes such as stabilisation, containment, and destruction of biodegradable contaminants. They also contribute to broader sustainability goals, such as reducing carbon footprints and preserving soil functionality, and can support site reuse for biofeedstocks, habitats, or amenity spaces. LIRT are particularly valuable for stalled or economically unviable sites, offering cost-effective and flexible solutions. However, achieving sustainable outcomes depends on site-specific factors, and LIRT often work best when integrated into a broader remedial strategy combining intensive and low-input methods. This paper explores LIRT's potential applications, technical characteristics, and challenges, alongside their benefits for sustainable land management and the restoration of underutilised sites.

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Environmental significance

Risk management that is also sustainable is global best practice for contaminated site remediation. While sustainability is always site-specific, some methods tend towards sustainability. Nature Based Solutions (NBS) and "Gentle Remediation Options" (GRO) encompass many of these. However, these categories overlook other promising approaches, such as *in situ* stabilisation. The paper proposes a broader umbrella term: Low Input Remediation Techniques (LIRT), *i.e.* methods that use fewer resources and less energy, may use or produce renewables, and can deliver added benefits beyond risk reduction (*e.g.*, biodiversity gains and social value). This review provides a framework for defining LIRT, surveys existing techniques, and outlines their wider value, aiming to broaden attention beyond biobased options and encourage wider uptake in practice.

[a]*r3 Environmental Technology Ltd, Chiltern Chambers, 37 St Peters Avenue, Caversham Heights Reading, UK. E-mail: paul@r3environmental.co.uk*
[b]*Division of Stockholm Convention, Foreign Environmental Cooperation Center of Ministry of Ecology and Environment of China, 5 Houyingfang Hutong, Xicheng District, Beijing, 100035, China. E-mail: lai.jinyu@fecomee.org.cn*
[c]*GreenDecision SRL, Cannaregio 5904, 30121 Venezia (VE), Italy*
[d]*CENSE – Center for Environmental and Sustainability Research & CHANGE – Global Change and Sustainability Institute, NOVA School of Science and Technology, NOVA University Lisbon, Campus de Caparica, 2829-516 Caparica, Portugal*
[e]*BRGM (French Geological Survey), BP 6009, 45060, Orléans Cedex 2, France*
[f]*Université Claude Bernard Lyon 1, Laboratoire d'Ecologie Microbienne, UMR CNRS 5557, UMR INRAE 1418, VetAgro Sup, 69622 Villeurbanne, France*
[g]*Waste Science and Technology, Luleå University of Technology, 97187 Luleå, Sweden*
[h]*GAU-Radioanalytical, School of Ocean and Earth Science, University of Southampton, National Oceanography Centre (Southampton), Southampton, SO14 3ZH, UK*

1 Introduction

In the frame of the Risk Based Land Management (RBLM) concept,[1] remediation describes interventions that are made to manage risks from land contamination.[2] Hence, the remediation of contaminated sites and brownfields has the core objective of reducing the human and environmental risk to acceptable levels for the intended use of the site.[3] Since mid-to-late 2000s growing interest for sustainable remediation has emerged,[4] which has been further stimulated by the need to pursue the objectives of the United Nations 2030 Agenda for Sustainable Development, and recently the objectives of the European Green Deal. All these strategies are pushing towards

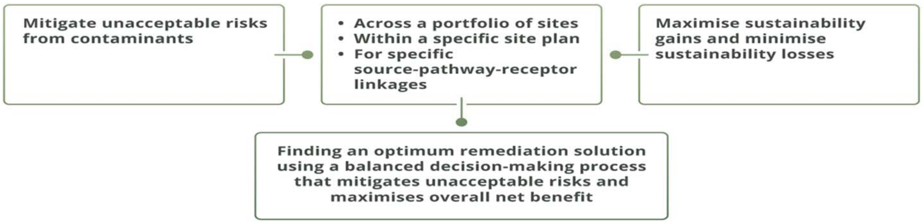

Fig. 1 Sustainable and risk based land management.

the development and implementation of integrated approaches which maximise the net benefits of remediation and minimise the negative impacts of such interventions.[5] Hence, the international consensus that has emerged in terms of best practice is that: (a) decisions regarding contaminated sites should be made based on understanding and managing risks to human health and the wider environment, taking into account the current or planned use of the land,[6] and (b) sustainability is a key consideration in determining the optimal approach to achieving the risk management needed,[7] as shown in Fig. 1. This shared understanding between regulators, site managers and service providers was crystallised in a joint statement of the key stakeholder networks NICOLE and COMMON FORUM,[8] and is increasingly recognised in international practice, policy, and regulation.[4] Critical in this best practice thinking is the concept of managing risks by breaking linkages between sources, pathways and receptors as shown in Fig. 2. These are commonly referred to as S–P–R linkages. This breakage may be achieved at the level of the source (*i.e.* source management, for example by excavation and removal), at the level of the pathway (*i.e.* pathway management, for example by monitored natural attenuation), or interventions at the level of the receptor (for example an institutional control limiting allowable land uses). Very often risk management combines interventions at more than one such "level".[2]

This paper introduces the concept of low input remediation techniques, LIRT, (see Fig. 3). Broadly, these are techniques with intrinsically low materials and energy intensity, (or which exploit renewable inputs). Moreover, these techniques typically also provide wider benefits than achieving risk management alone (for example improving soil health in parallel).

The concept of LIRT is not brand new. As early as the 1990s a related idea of "extensive" (as opposed to intensive remediation) emerged in the Netherlands,[9] although it was not much further advanced at that time. More recently the related concepts of gentle remediation options (GRO) and Nature-Based Solutions (NBS) have been developed.

• NBS deploy natural processes across soil, air, water and biology to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits.[10] A good example of such a societal challenge is the management of contaminated sites.

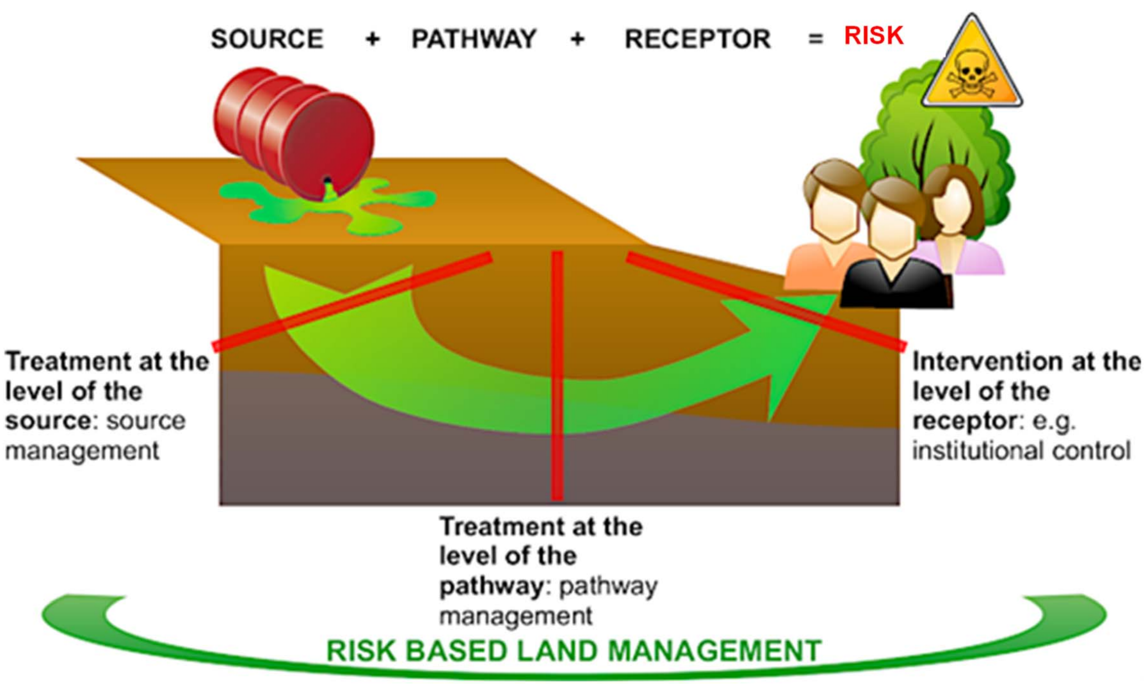

Fig. 2 Risk management along S–P–R linkages.

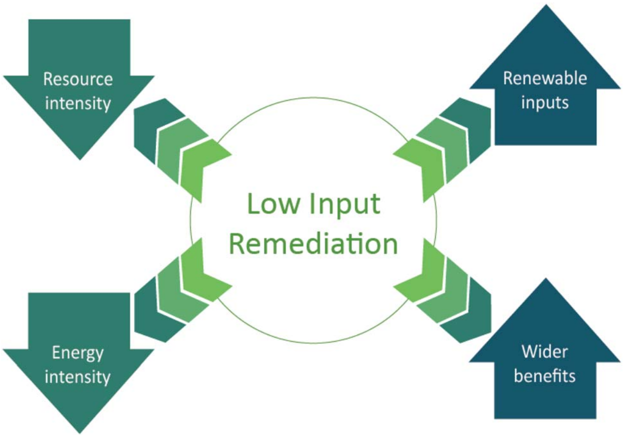

Fig. 3 Low input remediation main characteristics.

• GRO are risk management techniques which provide a net gain (or at least no net loss) in beneficial environmental, social and economic outcomes, such as soil function. GRO is primarily used to describe remediation that makes use of plants, microbes, and fungi to remove, sequester, immobilise or degrade contaminants.[11,12]

These primarily deploy for land contamination problems where the area is not sealed, and a functional soil is required.

Both concepts are focused on biological processes and on soil. Their philosophy is to highlight processes that might be intrinsically more sustainable in terms of their materials and energy intensity and their impact on soil. However, the goal of highlighting techniques which might be intrinsically more sustainable is equally relevant for groundwater management, where monitored natural attenuation[13] might be a candidate. Moreover, non-biological processes such as *in situ* stabilisation[14,15] might also have useful sustainability advantages; and the deployment of renewable energy might allow treatments such as electro-remediation to have a reduced carbon footprint.[16]

The advancement of LIRT is that it encompasses existing concepts such as NBS and GRO but expands the idea by highlighting techniques that might be associated with sustainability advantages to include groundwater remediation and remediation approaches that are not biological or solely biological in nature. LIRT are a "family" of approaches where we might expect lower energy and resource intensity, greater use of or production of renewables and wider benefits. The use of LIRT does not guarantee, *per se*, that a "sustainable solution" will occur. Sustainability depends on multiple site-specific factors,[17,18] for example, a local waste heat source may greatly change the sustainability picture for an *in situ* thermal treatment. However, low input remediation opportunities will tend to improve the net benefit in a contaminated site management project. Hence, while LIRT may possess intrinsic sustainability advantages, selection of the most sustainable remediation alternative is highly site specific. The use of an LIRT is not guaranteed to be the most sustainable remediation option for any particular problem. Comparative sustainability assessment[19,20] should always be used to understand the optimal remedial approach for a site,[21] as this determination is highly site and context specific. However, LIRT possess advantages which will tend to allow them to perform better under such assessments.

The remainder of this paper provides an overview of selected remediation technologies that can be classified as LIRT. This considers the contexts in which their deployment is most likely to be useful, their technical characteristics, application conditions, treatable contaminants, reasoning behind their classification as low impact remediation technology, and current technical challenges. This is followed by an examination of the broader benefits they can bring, for instance, in improving soil functionality, and how they can be deployed with important sustainable land-uses such as for biofeedstocks or social amenity. The paper then discusses broad challenges for the use of LIRT, but also their particular benefits for long term brownfields and contaminated sites.

2 Deployable low input remediation approaches

2.1 *In situ* stabilisation

In situ stabilisation is the introduction of amendments into the subsurface which chemically immobilise contaminants of concern, decreasing their availability to organisms, reducing their uptake, and making them less leachable by water. The LIRT features of this technique are a tendency to low energy and materials use intensity, the applicability of renewable or secondary resources, and wider benefits associated with low or positive impacts on soil health/function.

In situ stabilisation may be used in the vadose zone, for example within surface soils, and in the saturated zone, for example to reduce concentrations of dissolved phase contaminants.[2] If the contaminants are effectively immobilised, they are less likely to compromise other environmental compartments, such as aquifers or contribute to the migration of contamination plumes. The mode of immobilisation may be *via* sorption (physical and chemical interactions that weakly bind contaminants to a bulk substrate), fixation (chemical interactions that strongly bind contaminants to a bulk substrate), or both; *i.e.*, typically a process of sorption leading to fixation in the longer term. Fixation may be facilitated by redox processes, for example mediated by zero-valent iron (ZVI). The stabilisation effect may be reversible, for example if the pH of the subsurface becomes more acidic, leading to the desorption and remobilisation of contaminants, particularly trace elements. The extent of reversibility is smaller where contaminants have been "fixed". Reversibility may also be managed by ensuring there are no gross changes to subsurface pH or redox conditions. Resilience to reversibility may be designed into the amendment by changes in its formulation, often as part of proprietary products.[22]

In situ stabilisation may be regarded as a LIRT depending on (a) the nature of the amendment and (b) the way in which it is introduced. Examples of low input amendments include:

- Biochar;[23–26]
- Bone char/shell char;[24,27]
- Iron filings;[28]
- Minerals such as zeolites or clay minerals, depending on how they are sourced and where from;[29,30]
- Slags and other waste materials;[31,32]
- Composts, contaminants such as PAH's may be bound into humic materials,[33] however, the performance of composts can be inconsistent as some organic components can chelate trace elements increasing their mobility.[34,35]

An important feature for many of these amendments is that they can be produced from waste materials or by-products. For example, biochar can be produced from a wide range of waste materials such as from agriculture or forestry, such as rice husks, straws, woody materials. Moreover, biochar production can be associated with energy recovery, which maximises the sustainability gain from its deployment.[36,37]

Some caution is required in considering whether *in situ* stabilisation agents are sustainable with regard to their origin, the impacts of their extraction and degree of processing they require. Structured comparative sustainability assessment, for instance the SuRF-UK Framework,[20,38] is useful in unpicking how sustainable a particular *in situ* stabilisation approach is for a particular site.

The choice of amendment, from the perspective of risk management performance, is specific to the site conditions and the type of contaminant(s). Care also needs to be taken as some amendments may increase mobilisation (for example, as noted above, as a result of metal chelation with organic acids present in immature composts), or may contain entrained contaminants themselves, for example polycyclic aromatic hydrocarbons (PAHs) in biochars.[39] On the other hand, amendments may bring a range of wider benefits, for example, soil improvement by means of cation exchange capacity (CEC) increase, increase of pH buffering capacity, water holding capacity and increase of soil carbon content.

A major technical challenge for *in situ* stabilisation is introducing the *in situ* stabilisation agent into the subsurface. In some cases, where the targeted problem is contamination of topsoil, this may be achieved by simple cultivation (*e.g.* ploughing) processes using readily available agricultural machinery. However, where the contamination problem is deeper, or in the saturated zone, the introduction of the amendment is more difficult, typically *via* injection of suspensions of slurries. Injection is typically needed at multiple spots and care needs to be taken to ensure adequacy of coverage. One strategy for avoiding the need for multiple injection points, where a large area needs to be managed or the subsurface conditions are highly heterogeneous, is to use a treatment wall or permeable reactive barrier (PRB).[2] These applications can be used where the problem to be managed is off site migration of contaminants in groundwater. They allow for the introduction of the treatment agent into a carefully delineated *in situ* treatment zone which intercepts and treats contaminated groundwater flows. An innovative approach to introducing iron as an *in situ* stabilisation agent into the subsurface is *via* sacrificial electrodes.[40,41] Contaminants that can be treated by *in situ* stabilisation are reported in Table 1.

2.2 *In situ* bioremediation

Bioremediation is the application of biological processes to reduce the risk posed by contaminants to an acceptable level. There are a range of biological processes that can be exploited: degradation (the most commonly used in practice); biotransformation; immobilisation/accumulation and mobilisation. The LIRT features of bioremediation are a tendency to low energy and materials use intensity, the applicability of renewable or secondary resources, and wider benefits associated with low or positive impacts on soil health/function. However, this does depend greatly on the means of deployment. For example, deployment *via in situ* flushing is likely to have similarly high materials and energy intensities as pump and treat, whereas deployment *via* direct injection may be much less impactful.

The bioremediation ideal is for biodegradation to achieve complete conversion of contaminants into inorganic products (*e.g.*, CO_2, CH_4, Cl^-, N_2, *etc.*) – a process known as mineralisation. The biological conversion of contaminants into organic end-products can be equally acceptable, provided that the products are acceptable from the risk-assessment viewpoint. An example of bioconversion is the anaerobic remediation of chlorinated ethenes to yield ethene,[42] although ethene itself is aerobically biodegradable. In practice, most bioremediation processes will display both mineralisation and bioconversion to a greater or lesser extent.

Degradation may arise because an organic contaminant serves as a substrate for growth (or resembles one for the biological enzyme systems concerned, known as co-metabolism)

Table 1 Contaminants that can be treated by *in situ* stabilisation

Contaminant type as described in the Appendix	Source management	Pathway management
Biolabile	Immobilisation does not remove contaminants from the source term but renders them less able to migrate along exposure pathways	There are many types of stabilisation agents, which can immobilise ionic species and also organic species in the dissolved phase. Some forms of biochar may sorb wide range of organic and inorganic species. The effectiveness of the immobilisation is strictly dependent on extent of mixing of the agent into the subsurface. For the management of active plumes, deployment of stabilisation in PRBs may be an optimal approach
Persistent organic pollutants (POPs)	As above	
Trace elements	As above	

and as a source of electrons; or because it is a terminal electron acceptor that supports metabolism of another substrate. The most commonly exploited example of the second mode is dehalorespiration, which is now widely used to treat chlorinated solvents.[43]

Transformation is akin to bioconversion, which is the conversion of contaminants to hopefully less toxic forms, the most commonly applied biotransformation in practice is of chromium(VI) to chromium(III) which tends to be less mobile (and toxic) than chromium(VI) in the environment.[44]

Biological processes of immobilisation exploit the biological production of compounds that precipitate or sorb contaminants. One approach which has been attempted, at least at a demonstration scale, is the use of anaerobic production of sulphide ions to precipitate mobile metal species.[45] There is also interest in the sorption of organic contaminants (such as PAHs) to humic materials,[33] which are produced as a result of soil biological processes, and to organic structures produced during phytoremediation or possibly mycoremediation. Closely related (in terms of risk mitigation) is the ability of plant and/or fungal structures to accumulate contaminants, such as metals, and potentially in harvestable forms that can be removed from the subsurface.

Biological processes may also mobilise contaminants. The most exploited approach is the biological oxidation of sulphides to release acids that mobilise trace elements, also known as bioleaching, which is used in the mining sector.[46]

Biological processes are put into effect by one or both of biostimulation and bioaugmentation:[2]

• Biostimulation describes the alteration of *in situ* conditions to favour the microbial growth and activity that mediates the process of interest by one or more of the following:

• Altering oxygen availability (*i.e.*, redox), with some processes aerobic and others anaerobic;

• Improving nutrient availability;

• Improving contaminant accessibility/availability, for instance by adding surfactants;

• Supply of water;

• Temperature regulation;

• Providing microsites (for example to support biofilms).

Bioaugmentation describes the supply of specific microorganisms of interest to the subsurface to mediate required processes.[47] Non-specific bioaugmentation may also follow addition of amendments like compost. Bioaugmentation may be possible without whole organisms *via* the introduction of plasmid DNA.[48,49] Bioaugmentation can be performed using endogenous microorganisms already present in the contaminated site by enhancing the population of specific degraders, or by introducing exogenous microorganisms from other contaminated sites that are pre-acclimated to the target contaminant.

Bioaugmentation typically needs to be aided by biostimulation to support the activity of the introduced organism. However, the evidence in support of the effectiveness of bioaugmentation is rather mixed. There is robust evidence about the use of *Dehaloccoides* spp for enabling dehalorespiration of dichloroethylene,[50] and the use of bioaugmentation for the aerobic biodegradation of a range of chlorinated solvents to avoid the use of added substrate amendments.[51] However, in general bioaugmentation's validated track record is not as robust. The use of omics now provides a means of validating that introduced organisms are active in the subsurface[52] and this may extend the usefulness of bioaugmentation.

Both *in situ* biostimulation and bioaugmentation depend on the successful introduction of materials into the subsurface. There are a variety of means of doing this, as follows:[2]

• Cultivation may be used for the introduction of amendments to plough depth (15 cm), which may mediate biostimulation, bioaugmentation or both;

• Depositing amendments in excavations, for instance after removal of a tank; depositing materials in PRBs;

• Injection of slurries or liquid amendments is used primarily to emplace materials in the saturated zone;

• Flushing dissolved or suspended substances (or organisms) in the saturated zone *via* wells;

• Venting air and/or other gases in the unsaturated zone (bioventing);

• Sparging air and/or other gases in the saturated zone (biosparging);

• Plant rooting systems can support biostimulation, and may also support the introduction of specific micro-organisms, in particular mycorrhizae.

• Within the subsurface, compounds and organisms can continue to move through water, in the saturated zone.

LIRT approaches to bioremediation are those which achieve biostimulation and/or bioaugmentation with low materials and energy inputs. This assessment is, of course, somewhat subjective, with pumped and treat flushing based *in situ* bioremediation at one extreme (resource & energy intensive) and plant based biostimulation (phytostimulation) at the other. Sustainability assessment needs to be used to better compare different alternatives and their net benefits and impacts such as resource and energy use, as mentioned in Section 1.

The amendments used for promoting *in situ* bioremediation may have undesirable side effects on an aquifer, for example changing its pH or redox conditions, which may be necessary (for instance to stimulate dehalorespiration), but may have a wider impact outside of the treatment zone. These impacts may be subjective, for example, taint affecting the taste of water withdrawn from an aquifer some distance away.

A range of contaminants are treatable with *in situ* bioremediation: degradation of biolabile organic compounds, sorption of some more complex organic substances, transformation of some trace elements such as Cr(VI), and immobilisation or mobilisation of some trace elements, as reported in Table 2.

2.3 Natural attenuation and natural source zone depletion

Natural attenuation is a combination of naturally occurring processes that act without human intervention or enhancement that reduces risks posed by contamination in soil and groundwater. The LIRT features of this technique are a tendency to low energy and materials use intensity, the applicability of renewable or secondary resources, and wider benefits associated with more limited impacts on aquifer function.

Table 2 Contaminants that can be treated by *in situ* bioremediation

Contaminant type	Source management	Pathway management
Biolabile (biodegradable)	Biodegradation can be applied to residual source terms. However, application to free phase nonaqueous liquids (NAPLs) is often of limited effectiveness because of toxicity effects or because the contaminant is not bioaccessible	The principal application for *in situ* bioremediation
POPs	The effectiveness of biodegradation over short periods is limited as POPs are by their nature recalcitrant and partial biodegradation or biotransformation may yield more mobile/toxic daughter products. There is little information about treatability over long periods (*e.g.* decades) but combined biotic and abiotic processes in-ground is at least feasible	For source management
Trace elements	Biotransformation has been used for conversion of Cr(VI) to Cr(III), which is less mobile and less toxic. Biotransformation may also be useful for other trace element contamination problems, such as arsenic. However, at source terms toxicity may limit microbial activity	Well-established for Cr VI reduction and potentially useful for other circumstances where redox may render a trace element less mobile/ toxic. Relatively limited experience exists for techniques based on precipitation such as with biogenically produced sulphide

Natural attenuation processes include a variety of physical, chemical, or biological processes such as biodegradation, biotransformation, sorption, immobilisation, dispersion, dilution, volatilisation, and redox processes. The relative importance of these processes varies from site to site and within any plume as shown in Fig. 4.

Of these, being able to demonstrate that sufficient biodegradation is taking place is generally key to regulatory acceptance of natural attenuation for organic contaminants. If natural attenuation is to be part of a remediation process, its effectiveness needs to be demonstrated on a site-specific basis and monitored over time to validate that the desired risk management performance is occurring, hence becoming monitored natural attenuation (MNA). MNA may be deployed as a standalone pathway management process, most commonly in parallel with a source management process to reduce the flux of contamination entering a pathway.[2] While MNA is primarily considered a solution for biodegradable contaminants, a parallel concept has been proposed for natural attenuation of inorganic contaminants, relying on processes of sorption/immobilisation.[53] Monitored natural attenuation (MNA) offers a cost-effective, sustainable and robust technique for risk management of groundwater plumes, primarily for hydrocarbon impacted sites, but potentially also for gasworks and landfill sites.

Regulatory acceptance of MNA is dependent on a good dataset. A lines of evidence approach is used to support the case for and verify MNA, for example as described by the English Environment Agency,[54] considering loss of contaminant mass (primary evidence); geochemical and biochemical indicators, such as elevated CO_2, which demonstrate the natural attenuation processes (secondary evidence); and, at least initially, microbiological data to support the occurrence of biodegradation (tertiary evidence).

There is good agreement about the key parameters recommended for monitoring in broad terms. These are based on establishing primary and secondary lines of evidence, namely loss of contaminant mass (through determination of changes in contaminant concentration within individual boreholes and on the plume-scale, taking due account of plume variability) and geochemical and biochemical indicators which demonstrate the natural attenuation processes (principally through analysis of respiratory substrates and products). In some cases, for example less well understood contaminant types, tertiary lines of evidence are needed (direct demonstration of relevant microbial activity).

Natural source zone depletion (NSZD)[55] refers to the exploitation of natural attenuation processes described above to reduce the risks of light non-aqueous phase liquids (LNAPL) in the source zone, both residual sorbed LNAPL and sorbed LNAPL. As a practical risk management technique, the main goal of NSZD is to exploit these naturally occurring processes for the removal of LNAPL mass from the source term. These processes are primarily dissolution into groundwater over time (which gradually diminishes as more soluble components become depleted), volatilisation (eventually reaching atmosphere and gradually diminishing over time) and biodegradation.

MNA is primarily considered for groundwater (saturated zone) problems, whereas NSZD is applied to the source term across the unsaturated and saturated zones. NSZD is a relatively new approach with a developing track record.[56] Smith *et al.*[57] explain that in recent years NSZD has emerged as an important remediation approach for LNAPL sites. NSZD has its roots in Monitored Natural Attenuation (MNA) but with a different focus. MNA, originally developed in the 1990s, focuses on 'how far will a plume migrate' by identifying key attenuation fate and transport processes in the dissolved phase, determining plume stability (whether expanding, stable, shrinking, or exhausted), and evaluating indirect indicators of attenuation such as groundwater geochemical conditions. NSZD, a much newer remediation approach, focuses on 'how long will a plume/

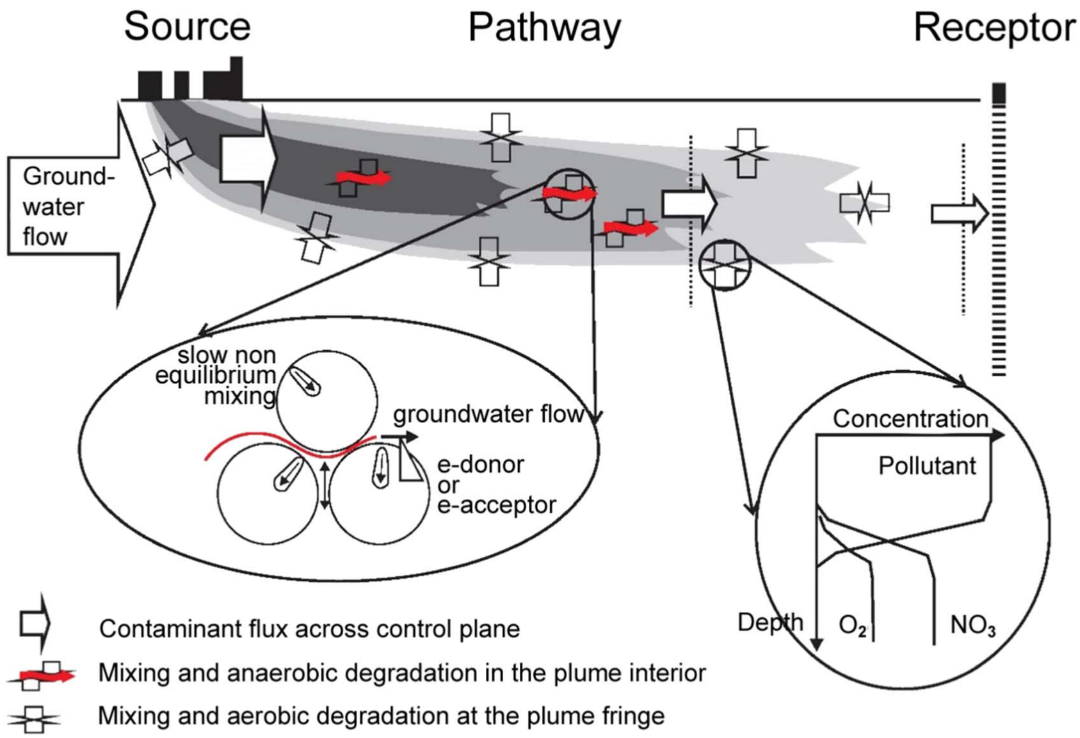

Fig. 4 A schematic diagram of a groundwater contamination plume showing core and fringe processes and placing MNA within the source-pathway-receptor risk assessment framework (credit prof. phil morgan and based on Banwart & Thornton, 2003; Thornton, 2017).

source zone persist' and is designed to measure the rate that LNAPL itself is depleted, either directly by LNAPL chemistry changes, or indirectly through soil gas, temperature or other suitable measurements.

Both techniques can be classified as LIRT, considering that external resources and energy requirements are very low or even not needed, while processes are naturally without human intervention or enhancement.

As far as target contaminants are concerned, MNA is primarily used for biolabile contaminants, but over time may also confer benefit for recalcitrant compounds and inorganic contaminants, as reported in Table 3, while NSZD is primarily used to treat LNAPL hydrocarbons, as reported in Table 4.

2.4 Electro-remediation

Electro-remediation exploits physical and chemical processes caused by an induced electric field. It may also be referred to as electrokinetic remediation. Modifications and new advancements of this technology have introduced LIRT features, such as reduced energy and material use[40,58–60] and its sustainability could be further enhanced by employing renewable energy sources.[16]

Physical processes depend on the induced movement of anions to anode and cations to cathode, which indirectly can lead to mass flow of groundwater. Electromigration, electroosmosis, and electrophoresis are the three primary transport processes responsible for moving contaminants from the matrix towards one of the electrode compartments. The movement of electrons can also facilitate *in situ* biological processes,[61] see Section 2.7.

Chemical processes include electrochemical reactions at electrodes and reactions mediated by changes in pH and redox caused by free radicals generated at the electrodes, as well as the supply of electrons.[16,62] At the electrodes, water electrolysis occurs, with oxidation taking place at the anode and reduction at the cathode.[63] This process generates hydrogen ions (H^+) at

Table 3 Contaminants treatable by MNA

Contaminant type	Source management	Pathway management
Biolabile	MNA is not a source management technique	The principal application for MNA
POPs	As above	There is little information about treatability over long periods (*e.g.*, decades) but combined biotic and abiotic processes in-ground is at least feasible
Trace elements	As above	MNA has been considered for trace elements, although – of course – these are not biodegradable.[53]

Table 4 Contaminants treatable by NSZD

Contaminant type	Source management	Pathway management
Biolabile	Increasing use in practice for hydrocarbons (*e.g.*, petroleum hydrocarbons)	Can operate in tandem with MNA
POPs	Not applicable	Not applicable
Trace elements	Not applicable	Not applicable

the anode and hydroxide ions (OH^-) at the cathode, resulting in acidic pH near the anode and alkaline pH near the cathode.[61]

Electrokinetic remediation methods were originally developed for the extraction of metal contaminants from soils, sediments, and sludges.[64–66] Over time, the scope of electrokinetics expanded to address chlorinated and non-chlorinated volatile and semi-volatile organic compounds by promoting the dispersion of amendments required to trigger chemical oxidation or reductive dechlorination processes.[65] More recently, these techniques have been applied to a broader range of organic pollutants, including petroleum hydrocarbons (such as diesel, gasoline, kerosene, and lubricating oils), polycyclic aromatic hydrocarbons (PAHs), and dense non-aqueous phase liquids.[66–69]

For metals, effective removal necessitates their solubilization through the addition of acids or complexing agents.[70,71] However, this approach is hindered by the need for significant soil acidification to prevent metals from reaching zones with basic conditions, where they usually adsorb onto soil particles or precipitate.[64] Interestingly, this challenge has recently been leveraged to intentionally precipitate inorganic contaminants within soil.[40,41] In such cases, corroding iron electrodes were employed as a source of iron precipitates to immobilize arsenic and other trace elements in contaminated soils, or generate subsurface Fe-rich barriers to groundwater flow in the treated soil.

These processes require significantly less power than what is typically needed to mobilize metals toward the electrodes, making it feasible to utilize renewable energy sources such as solar power. Moreover, the use of low voltage potentials (*e.g.*, 0.15 V cm^{-1}) can be advantageous for soil bacteria that contribute to the co-degradation of organic pollutants directly within the soil.[72–74]

Thus, the use of low current electro-remediation can be a LIRT, especially when powered by electricity provided from photovoltaic (PV) sources to reduce the carbon footprint of electro-remediation. However, the success of this strategy depends greatly on the type of electrokinetic approach being deployed, with PV based systems obviously being far better suited to lower current intensity applications.[75–77] Sacrificial (scrap iron) electrodes may also be used, for example, applied to arsenic immobilisation.[40]

Contaminants that can be treated by electro-remediation are reported in Table 5. The application of electrokinetic remediation to uranium and nuclear sector wastes, including potential for deployment using PV-based power supply, has been examined in the Horizon Europe SURRI project[78] and the UK TRANSCEND project.[12]

2.5 Phytoremediation

Phytoremediation is the direct use of plants and their associated microorganisms (phytomanagement) to stabilise or reduce contamination in soils, sludges, sediments, surface water, or ground water, and may create opportunities for biomass re-use and a range of other wider benefits.[2] There are different variants of phytoremediation with different applications, advantages and disadvantages. There are different opinions about how to subdivide this technology, but the technology variants below provide comprehensive coverage. All the phytoremediation options presented below can be classified as LIRT, when appropriately designed and implemented. They exploit the low resources and energy requirements of the involved processes which use plants, plant roots and their associated microorganisms, trees, living or dead plant biomass, *etc.* to treat soil and water contamination. Six of these options are described in the next sections. The LIRT features of this technique are a tendency to low energy and materials use intensity, the potential applicability of renewable or secondary resources such as composts, and wider benefits associated with low or positive impacts on soil health/function as well as the potential production of exploitable biomass.

2.5.1 Phytoextraction. Phytoextraction primarily describes the removal of trace elements from soils by accumulating them in the biomass of plants. Phyto-extraction exploits a wide range of plants and trees. A group of plants known as hyper-accumulators have been of particular interest as these have

Table 5 Contaminants that can be treated by electro-remediation

Contaminant type	Source management	Pathway management
Biolabile	Potentially applicable where linked to stimulating *in situ* redox	Potentially applicable where linked to stimulating *in situ* redox
POPs	Potentially applicable where linked to stimulating *in situ* redox	Potentially applicable but largely untested
Trace elements	Potentially applicable but may require high energy inputs	The typical application for low input electrokinetic based systems

physiological mechanisms that lead to high trace element concentrations in their tissues.[79,80] Attempts may be made to increase phytoextraction rates by adding mobilising agents to the soil and electric fields.[81,82] Practical delivery of phytoextraction is relatively limited by two constraints, despite multiple large scale field trials.[83] The first is that removal rates can be relatively slow, with estimates for source term removal being in the order of decades. The second is that the biomass harvested may be regarded as a waste and its use subject to restrictions. However, in the context of risk management, phytoextraction may be particularly effective for pathway management as, at least within the rooting zone, mobile trace element contamination is rapidly removed.[11,84] This may be particularly useful for diffuse surface contamination, for example from fallout or past use of biocides.

2.5.2 Rhizofiltration (engineered wetlands). Rhizofiltration describes the removal of pollutants from aqueous sources, for example drainage water from contaminated sites, by plant roots and their associated microorganisms. It can deal with a wide range of inorganic and organic contaminants. Engineered wetlands are a widely used manifestation of this approach.[85] In practice, rhizofiltration is a catch all for phytoextraction, phytodegradation, phytostablisation and phytovolatilization. However, it is also the phytoremediation approach that has seen the greatest practical deployment in the form of engineered wetlands,[86,87] and as a pathway management tool deals well with issues of runoff from diffuse contaminated sites.[88]

A recently started European project, LIFEPOPWAT,[89] combines low input *in situ* chemical and biological filters such as wood chip, peat, composts and iron filings, with engineered aerobic wetland to treat drainage water from a HCH (lindane) waste landfill. The landfill is also located in a former uranium mine. It is not economically feasible to deal with the source term, and even if it were, the processes used might have unacceptable wider sustainability impacts (such as vehicle movements or secondary emissions). Therefore, risk management effort has been focussed on pathway management of the landfill's drainage water, using an engineered wetland, integrated with low input *in situ* treatments at the front-end, called "Wetland+". The Wetland+ system is composed by three subsequent steps: an iron-based permeable reactive compartment, biodegradation and sorption unit and aerobic wetland system as reported in Fig. 5. Sustainability claims for the Wetland+ deployment at this site have been supported by a wide-ranging sustainability assessment, and environmental claims backed up by life cycle assessment.[90,91]

2.5.3 Phytovolatilisation. Phytovolatilisation describes the use of plants to take pollutants from soil and release them into the atmosphere. This has seen deployment in practice, particularly in the USA. A very common application is to treat organic compounds in shallow groundwater using tree species such as poplar.[92] A drawback of this approach can be the transference of a contaminant from one medium (groundwater) to another

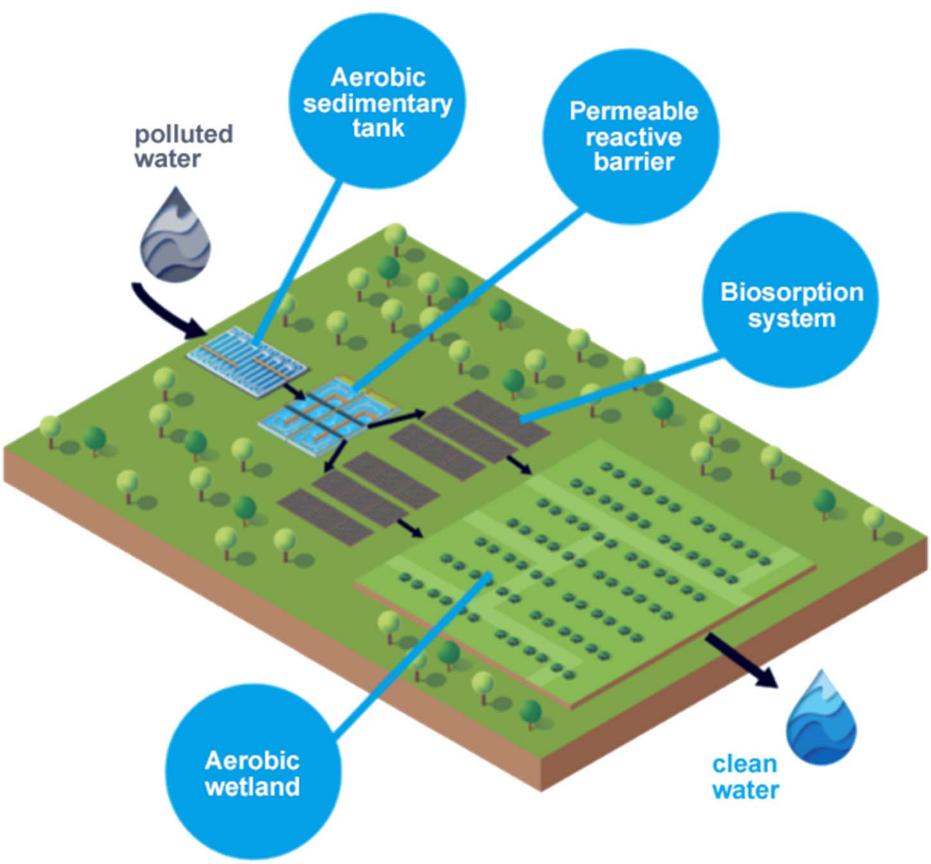

Fig. 5 Wetland+™ schematic, © Technical University of Liberec.

(air), and this may be problematic both in terms of risk transference and sustainability.

2.5.4 Phytostabilisation. Phytostabilisation describes the reduction in the bioavailability of pollutants by plants through their immobilisation on living or dead plant biomass, biomass from associated organisms (*e.g.*, mycorrhizae) or components that have become soil humus, and can be enhanced by use of soil amendments.[93,94] It has potential applications for organic and inorganic contaminants. The extent of practical deployment for site remediation in practice appears to still be relatively limited.

Phytostabilisation and *in situ* stabilisation might be deployed in parallel with a view to maximising immobilisation of trace elements.[95] However, it is possible that *in situ* stabilisation using biochar might increase trace element uptake into biomass because it supports improved plant growth in general.[96] This additional uptake may be problematic if the biomass is to be re-used, for instance, for energy.

2.5.5 Phytocontainment. Phytocontainment is the use of plants to facilitate the isolation of contaminants, particularly surface contamination.[97] It is practically deployed very frequently in conjunction with cover systems, or indeed to substitute for conventional cover systems that are based on geomembranes and aggregates.[2] For example, phytocontainment can be used on former mining sites or tailing dams after suitable surface amelioration, to prevent erosion of mining waste and the exportation of contaminated particles. This approach is often described as vegetative cover.[97,98] It is used as a pathway management tool for a wide range of contamination problems. However, it does not address source term issues.

2.5.6 Phytoexclusion. Phytoexclusion describes the implementation of a stable vegetation cover using plants which do not extract contaminants, which can be combined with *in situ* immobilisation, as a pathway management technique.[99] It could allow the re-use of a site, for instance, to produce non-food crops.[83] At this point it is more or less a conceptual approach, with limited investigation.

Contaminants that can be treated by the six phytoremediation options described in the previous sections are reported in Table 6.

2.6 Permeable reactive barriers

Permeable Reactive Barriers (PRBs) are a broad range of approaches where some form of *in situ* treatment zone is placed

Table 6 Contaminants that can be treated by the six phytoremediation options

Phytoremediation options	Contaminant type	Source management	Pathway management
Phytoextraction	Biolabile	Biodegradation based approaches are more suitable	Biodegradation based approaches are more suitable
	POPs	Potentially applicable for diffuse contaminated zones, but largely untested	Potentially applicable for diffuse contaminated zones, but largely untested
	Trace elements	Applicable, but mostly over long time periods	The most suitable application for phyto-extraction
Rhizofiltration	Biolabile	Not applicable	Well documented in practice
	POPs	Not applicable	Well documented in practice
	Trace elements	Not applicable	Well documented in practice
Phytovolatilisation	Biolabile	Potentially applicable to residual source terms but possibly limited by phytotoxicity	Well documented in practice
	POPs	Not applicable	Not applicable
	Trace elements	Not applicable	Not applicable
Phytostabilisation	Biolabile	Biodegradation based approaches are more suitable	Biodegradation based approaches are more suitable
	POPs	Potentially applicable for diffuse contaminated zones, but largely untested	Potentially applicable but largely untested
	Trace elements	Potentially applicable but may be limited by phytotoxicity	Potentially applicable
Phytocontainment	Biolabile	Biodegradation based approaches are more suitable	Biodegradation based approaches are more suitable
	POPs	Potentially applicable, and has been deployed in practice, but effectiveness not yet well validated	Potentially applicable, but largely untested
	Trace elements	Potentially applicable, and has been deployed in practice, but effectiveness not yet well validated	Potentially applicable, but largely untested
Phytoexclusion	Biolabile	Biodegradation based approaches are more suitable	Biodegradation based approaches are more suitable
	POPs	Potentially applicable, but largely untested	Potentially applicable, but largely untested
	Trace elements	Potentially applicable, but largely untested	Potentially applicable, but largely untested

Table 7 PRBs: treatable contaminants in practice

Contaminant type	Source management	Pathway management
Biolabile	Not applicable (PRBs are by default a pathway management technique)	Readily applicable
POPs	Not applicable	Applicable and demonstrated
Trace elements	Not applicable	Readily applicable

in the natural direction of groundwater travel, or groundwater is funnelled to such a treatment zone. Within this treatment zone, contaminant degradation, immobilisation or removal is achieved, and groundwater flow is relatively unimpeded.[2,100] It is a pathway management technique, primarily for groundwater. PRBs exploit natural groundwater flow, as opposed to more intensive systems where active groundwater pumping takes place and/or above ground treatment. The use of PRBs avoids both the energy and resources needed for more active systems and also avoids the need to discharge or re-infiltrate pumped water. There are applications for both organic and inorganic contaminants (see Table 7). PRBs are usually deployed where the source term is relatively intractable (for instance because of scale or difficulty in access) or will take time to treat. Moreover, natural materials can be used as sorbents in PRBs to provide immobilisation and support subsequent biodegradation. An example substitution for pump and treat is described in a recent sustainable remediation case study.[101]

The sustainability of PRB use is highly site and project specific, depending on the type of configuration used and the material and energy demands of its deployment. However, there are energy and material intensity reduction benefits potential possible because natural groundwater flow paths are used, so pumping is not needed, along with scope to use renewable or secondary resources in PRB construction. Wider benefits accrue because the treatment intervention is more localised rather than needing to be deployed across a very large aquifer area.

2.7 Bioelectrochemical remediation (BER)

Bioelectrochemical remediation (BER), see Fig. 6, is based on microbial bioelectrochemical systems in which an anode and a cathode favour redox reactions that are catalysed by microorganisms.[102] The prototype of a bioelectrochemical system is the microbial fuel cell (MFC) that generates electricity based on organic matter oxidation in the anode chamber. Oxygen is used as electron acceptor in the cathode compartment or at the air-cathode. Oxygen in air has effectively unlimited availability and a high standard redox potential. In addition, the bioelectrochemical system can use a small amount of energy to fuel chosen reactions in the cathode chamber. In this case, in the cathode chamber electrons released from the cathode can be exploited for uses other than oxygen reduction. The biocatalytic principle of a bioelectrochemical system contributes to drive local thermodynamically unfavourable reactions by their connection to a driving force. In the case of petroleum hydrocarbon degradation (oxidation) at the (anaerobic) anode, the electrons are siphoned away through the electrical connection to the aerobic cathode where molecular oxygen is present. Thus, the anode plays the part of an alternative electron accepter for improving hydrocarbon removal, for example,

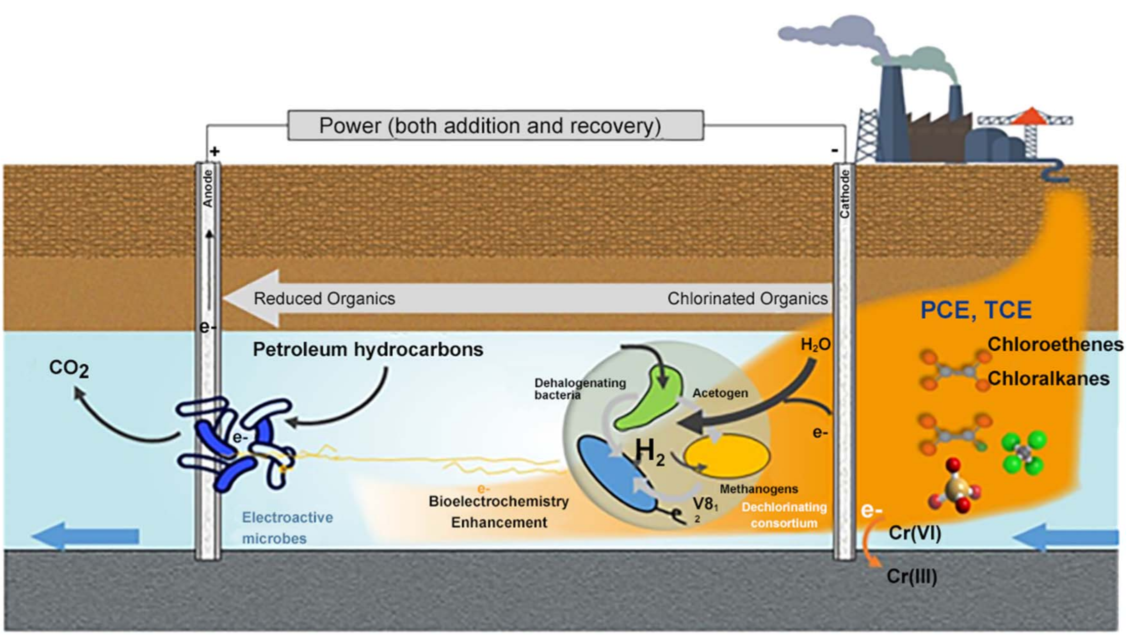

Fig. 6 Bioelectrochemical remediation concept.

Table 8 Bioelectrochemical remediation: treatable contaminants in practice

Contaminant type	Source management	Pathway management
Biolabile	Potentially applicable, tested at lab & pilot scale	Not applicable as substrate concentrations unlikely to be sufficient
POPs	Potentially applicable	Not applicable as substrate concentrations unlikely to be sufficient
Trace elements	Not applicable	Not applicable

to achieve significant performance improvements over conventional anaerobic bioremediation.

The technology benefits from the bioelectrochemical conditions at both the anode and the cathode. At the anode, the anaerobic oxidation of reduced organic compounds (*e.g.*, petroleum hydrocarbons) will be enhanced by the electron acceptor (the anode itself), thus reducing possible sulphate reduction and methane production under anaerobic conditions. At the cathode, reduction reactions will occur such as the dechlorination of chlorinated compounds and the reduction of potentially toxic elements, *e.g.*, CrVI to CrIII. Table 8 summarises the range of potential applications.

The LIRT features of this technique are its low energy and materials use intensity, the potential re-usability of some system components, and its wider benefits associated with low or positive impacts on aquifer function.

3 Emerging low input remediation approaches

The LIRTs reported in the next sections are examples of emerging research in this field and can be classified as LIRT in consideration of the low resources and energy requirements of the involved processes which use fungi, plants, plant roots and their associated microorganisms, *in situ* redox reactions associated with phytoremediation and redox reactions catalysed by microorganisms to treat soil and water contamination. The LIRT features of these techniques are a tendency to low energy and materials use intensity, the potential applicability of renewable or secondary resources such as composts, and wider benefits associated with low or positive impacts on soil health/function as well as, in some cases, the potential production of exploitable biomass.

3.1 Mycoremediation

The exploitation of fungi in remediation processes is relatively under-explored.[103] Many basidiomycete fungi (for instance white rot fungi) use extracellular enzymes and excreted hydrogen peroxide to digest lignin. This system is relatively nonspecific (see Table 9) and its potential for degrading complex organic contaminants such as PAHs was recognised from the 1990s and it was trialled (*ex situ*) at relatively large scale[104,105] and has since re-emerged.[106] Academic interest in mycoremediation for organic contaminants remains, for example for treating POPs such as dioxins,[107] however scale up to practical use remains elusive. Fungi also interact with trace elements and can play a role in the mobilisation or immobilisation of trace elements, which may influence processes of phytoremediation, see Section 4.6.[108] The most likely scenario for mycoremediation in practice will be the role of mycorrhizae within phytoremediation, for example in biodegradation or improving phytoextraction.[109–112]

3.2 Phytodegradation/rhizodegradation

Phytodegradation/rhizodegradation describes the use of plants and associated microorganisms such as root-zone bacteria to degrade or transform contaminants (see Table 10). Plants may affect microbial biodegradation in several ways,[113] including:

• Mobilisation of contaminants may take place *via* production of organic ligands for trace elements, changing pH, redox potential. This may be as a direct consequence of components in root zone exudates such as organic acids or the stimulation of commensal organisms such as pseudomonads which in turn release ligands such as siderophores.[114] Roots may also release surfactants,[115] which may mobilise organic contaminants. This mobilisation may be important in supporting both phytoextraction or biodegradation.

• Biostimulation assists commensal micro-organisms in the vicinity of roots, changing pH, providing substrate (*e.g.*, *via* root exudate) changing redox, pCO_2. This biostimulation is local and supports aerobic processes, potentially including cometabolic processes, as roots are generally in aerobic soil zones. While there is significant academic discussion of biostimulation in the root zone for remediation (*e.g.* Correa-García *et al.*[116]), there are few widely known practical deployments in the field and the potential of co-metabolic processes is under-explored.

Table 9 Mycoremediation: treatable contaminants in practice

Contaminant type	Source management	Pathway management
Biolabile	Potentially applicable for diffuse contaminated zones	Potentially applicable
POPs	Potentially applicable for diffuse contaminated zones	Potentially applicable
Trace elements	Potentially applicable for diffuse contaminated zones linked to phytoremediation	Potentially applicable for diffuse contaminated zones linked to phytoremediation

Table 10 Phytodegradation/rhizodegradation: treatable contaminants in practice

Contaminant type	Source management	Pathway management
Biolabile	Potentially applicable to residual source terms. However, application to free phase nonaqueous liquids (NAPLs) is often of limited effectiveness because of toxicity effects or because the contaminant is not bioaccessible	Potentially applicable
POPs	Potentially applicable for diffuse contaminated zones, but largely untested	Potentially applicable, but largely untested
Trace elements	Not applicable	Not applicable

• Supporting symbiotic organisms (*e.g.* mycorrhizal fungi, rhizobia), and possibly acting as a conduit for bioaugmentation, see Sections 4.2 and 4.4. Bioaugmentation techniques have also been investigated[117] for the introduction of rhizobacteria and mycorrhizal fungi.

• An emerging idea is whether pioneer species that spontaneously appear on a brownfield or contaminated site can show phytodegradation potential,[118] in a similar fashion to the spontaneous appearance of biodegradation processes underpinning monitored natural attenuation (see Section 2.3).

3.3 Enhanced phytoremediation

The EU-China EICLAR project[119] explored a group of technologies combining electrokinetically (EK) stimulated *in situ* redox reactions and enhanced mobility with phytoremediation to provide low input remediation of hydrocarbons, including some persistent types, in parallel with immobilisation of trace elements (see Table 11). The treatment is intended for use on large area sites combining plant-supported *in situ* biodegradation in the rooting zone with deeper treatment by chemical degradation, and plant-based management of fugitive VOCs from that process (see Fig. 7). The use of sacrificial iron electrodes can also be included to immobilise some trace elements *in situ* with iron oxide complexes. Mycorrhizal fungal amendments are being considered to support plant establishment and to provide lignase-based bioremediation to target recalcitrant compounds such as PAHs. Other approaches to enhancing phytoremediation (outside EiCLaR) include the use of electrokinetics to mobilise metals for plant uptake.[120]

4 Broader benefits that can be delivered by low input remediation techniques

Managing risks to human health, water, ecology or other receptors is the principal driver for remediation taking place. In practical terms many sites might combine low input remediation with more intensive remediation, for instance, to deal with individual source term "hotspots". The possibility that low input remediation achieves a more rapid return to the natural ecosystem, even if the treatment phase is longer, also needs to be considered.[121] In many cases, LIRT can also bring additional benefits beyond risk management, which can further improve the economic case for restoration of economically marginal sites[21,122] and are described in the next sections.

4.1 Soil improvement

LIRT can provide a unique and currently underused opportunity to generate revenue through cultivation of plants or crops (for biomass/biofeedstock, either green infrastructure or crop growth), ecological habitat or public open space. An important first step in this direction is to improve the soil to sustain the desired vegetative cover or ecological trajectory. In order to sustain revegetation of a site, a soil must be of sufficient quality, considering:

• Condition (physical and chemical properties of the soil and its structure),

• Fertility (taking into account the soil's ability to supply plant nutrients such as nitrogen, phosphorous, potassium, magnesium, calcium and sulphur and micronutrients; soil

Table 11 Enhanced phytoremediation: treatable contaminants in practice

Contaminant type	Source management	Pathway management
Biolabile	Potentially applicable to residual source terms. However, application to free phase nonaqueous liquids (NAPLs) is often of limited effectiveness because of toxicity effects or because the contaminant is not bioaccessible	Potentially applicable where linked to stimulating *in situ* redox
POPs	Potentially applicable for diffuse contaminated zones, but largely untested	Potentially applicable, but largely untested
Trace elements	Potentially applicable for diffuse contaminated zones, but largely untested	Potentially applicable, but largely untested

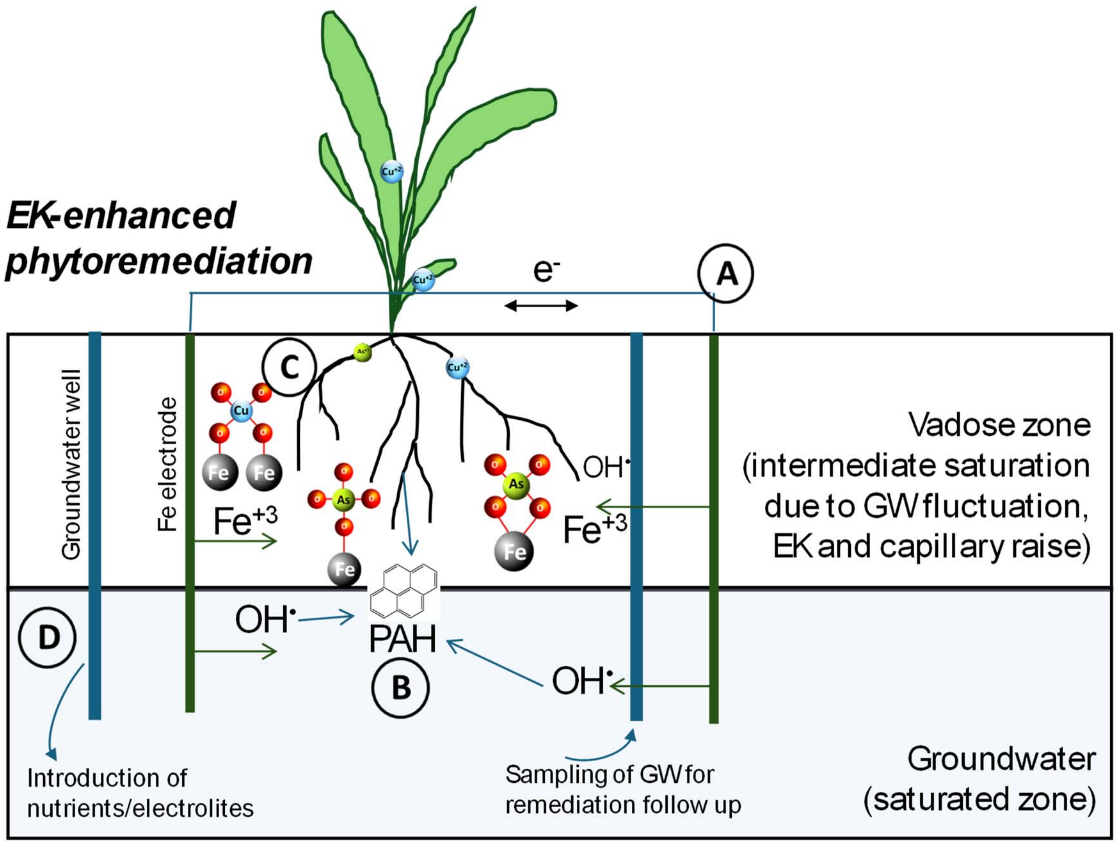

Fig. 7 Enhanced phytoremediation concept (A) iron electrodes are inserted through the vadose zone into the groundwater layer and a range of EK inputs are applied using pulsed DC current. (B) Bioavailability and biodegradability of recalcitrant organic contaminants increases by eletrokinetic (EK)-initiated desorption and degradation, which accelerates phytoremediation through rhizodegradation. AMF helps plant establishment, adds to biostimulation, and potential lignase activity. (C) Mobile and bioavailable fractions of metal (loid)s are immobilized through co-precipitation with iron provided by sacrificial iron electrodes. It might be favorable to maintain the electrical current until the treatment is fully completed to prevent any potential migration of metal (loid)s into groundwater. EK further modifies soil conditions (supply of oxygen, decreased contaminant toxicity) to favour plant establishment. (D) Nutrients are supplied to deeper soil layers to enhance microbial processes at depth. Vertical integration PR favoured at shallow depth, EK works at a deeper level.

fertility can have a strong connection to its biological functionality) and

• Depth (which must accommodate plant rooting depth). It is possible that the required soil properties will change with depth.

Soil improvement is discussed in more detail in the context of biomass production in Bardos *et al.*[83]

As a service, soil improvement describes processes of enhancing soil condition and fertility. Soil on contaminated and brownfield sites may be of poor quality and structure, especially on sites that have previously been developed for a “hard use”. In many such cases, the soil may be no more than ‘made ground’ (such as demolition rubble, “fill” or even subsoil) which is of poor quality and structure and is unlikely to support vegetation. Soil improvement may also be necessary to deliver services such as biomass cultivation and the provision of some forms of green infrastructure, based on revegetation.[123]

4.2 Water resource management

LIRT can help improve water resource management, as part of a wider site risk management strategy. Potential benefits can be one or more of the following depending on the site context:

• Supporting sustainable drainage (*i.e.*, drainage down to groundwater resources rather than *via* sewerage to surface water which in turn reduces flood risks and drainage capacity and treatment requirements).

• Providing capacity for flood protection *via* retention of surface water runoff and water storage and flood mitigation, for example in revegetated areas, even those used for public amenity. This may be of increasing value as society needs to be better able to respond to extreme weather events as a result of human-induced climate change.

• Providing the potential for wastewater treatment, for example, *via* phytoremediation of irrigated landfill leachate or other wastewaters, subject to acceptable risk assessment.

• Reduced flux of contaminants to aquifers and surface water over long periods.

4.3 Renewable energy

LIRT present opportunities for integrating remediation activities with the installation of renewable energy facilities such as wind power, solar power, bioenergy and geothermal energy. The energy generated can be utilized directly in the remediation process or can be sold, providing additional economic income. The installation of renewable energy on contaminated sites or brownfield sites reduces the consumption of pristine land, such as agricultural land, for green energy. Brownfield based renewables has particularly been exploited in the USA.[124]

Wind power generation can also be easily combined with several other uses on the regenerated sites; *i.e.* residential, commercial and other soft re-use such as parks and gardens (allotments). The presence of wind turbines in urban areas may offer better efficiency as losses due to transport of energy on long distances are minimised.

Phytoremediation may be implemented in a way that the biomass generated during remediation activities or on the remediated sites can be directly used in energy production (by anaerobic digestion or thermal conversion), or by further production to generate biofuels.

In former mining areas, volcanic areas and sedimentary basins there is sometimes potential to recover energy from geothermal heat sources using heat pumps by drilling into the ground, and then transport this energy to the surface using fluids with high (greater than 150 °C), medium (90–150 °C) and low (less than 90 °C) temperature. With the recent accelerated deployment of variable power from wind and solar photovoltaic, geothermal can contribute to the stabilisation of electricity grids. In addition, geothermal energy technology has evolved beyond its focus on the electricity market to encompass a broader range of applications within the energy sector, including for sustainable heating and cooling.[125]

These renewable energy opportunities may be deployed as an interim site use while long term low input remediation takes place, or energy recovery may be directly from phytoremediation biomass.

4.4 Biofeedstock

Biomass produced during or after the remediation activities took place, including phytoremediation biomass, may also be reused as a biofeedstock for industrial chemicals (such as methanol or ethanol),[126] as a source of fibres that can replace less sustainable fibres like glass fibres,[127] feedstocks for bioplastics production[128] and also, depending on the site context, high value products such as nutraceuticals.[129]

4.5 Green infrastructure and ecological gains

LIRT can provide a unique and currently underused opportunity to deploy green infrastructure for the enhancement of ecosystem services and local environments.

Green infrastructure describes a strategically planned and delivered network of high-quality green spaces and other environmental features, possibly delivering multiple benefits for both nature and society. Green infrastructure enhances ecosystem services and the local environment. Examples include: protection of habitat and biodiversity (where existing and for protected sites); developing new habitat and increasing biodiversity; improving urban soundscapes and air quality; limiting visual intrusion by landscaping (buildings, transport links *etc.*); urban climate management (such as mitigation of urban heat island effect). Provision of green infrastructure may be an important policy driver for Public Sector investors in contaminated sites and brownfields regeneration. While provision of green infrastructure may be antagonistic with other uses of land area, for example for biomass production, combined approaches are possible, for example, by taking a mosaic design to the landscape. Mosaics are typically applied to describe a diversity of ecologies on a brownfield[130] or in describing a range of land uses in spatial planning over an area.[131] At the scale of a brownfield site, a similar diversity of uses may be created, for example combining functions for amenity, habitat, renewables and built environment, obviously depending on scale.

4.6 Circularity

Contaminated sites management has two key circular economy linkages. (a) In the context of brownfields, a circular economy for land is a major policy goal in most countries, with many compelling arguments for encouraging the reuse of previously used land rather than greenfield developments.[132] (b) In the context of excavated materials, natural soil is essentially a non-renewable resource because of the length of time required for soil formation on bedrock, so there are also important benefits in securing the re-use of excavated soil to avoid extraction of virgin materials such as topsoil or aggregates. Soil improvement to improve soil functionality, may also make use of local recyclates such as composts.[133]

The circular economy perspective is also very relevant in the context of the use of resources during remediation processes,[134] as well as the generation of resources by land-use and including contaminated sites management. The key principles of the Circular Economy (CE) delineate the strategic approaches necessary to drive circular actions[135] and have been formally integrated into policy frameworks in the European Union[136] which have evolved into hierarchical structures[137,138] comprising various actions which can be measured by means of appropriate circularity indicators.[139,140]

Considering the intrinsic characteristics of LIRT, their role in advancing the CE is particularly significant in the context of reducing the consumption of material and energy resources. Moreover, the contribution of LIRT extends to post-intervention phases by enabling the reuse of materials and resources that might otherwise be discarded as waste. Low input remediation, such as phytoremediation, offer opportunities as they are relatively frugal in their use of resources and energy, and provide biomass which can be used for energy or biofeedstock. Additionally, the regeneration of contaminated sites and brownfield sites may produce a range of renewable material opportunities, creating significant revenue opportunities, including the reuse of excavated materials and demolition materials generated during site restoration. Excavated materials may be repurposed as aggregate or fill materials, including where they have been treated by *ex situ* remediation processes.[141]

4.7 Economic gains

LIRT application can bring economic gains related to direct revenue from biofeedstock or energy produced on site.

Economic gains may also accrue from avoided land costs, in particular for public budget holders, as they can use the remediated land for purposes like flood management capacity or renewables, rather than look for land resources from more expensive agricultural or peri-urban land. Over the long term there may be economic uplift for the site itself as its value increases, for instance because it has renewable energy production sited on it, or as low input remediation gradually reduces recalcitrant POP contamination.

There are also intangible economic benefits, with potentially a substantial economic value[142,143] for example from the following:

• Property value uplift in surrounding areas;

• Avoided public health budget, as land restoration provides opportunities for outdoor recreation resulting in better well-being and health for citizens;

• Carbon storage, for example by increased carbon sequestration in the subsurface or as a standing crop of vegetation, and fossil carbon substitution through the production of renewables;

• Providing a "green" framing for built redevelopment, increasing the value of the buildings because they are sited in a more attractive and functional landscape. The buildings themselves can be made more sustainable (for instance by the supply of green energy or making available sustainable urban drainage for grey water).

4.8 Societal gains

The implementation of low input remediation can support major societal gains, in particular for Type C sites, for example the linkage of landscapes and phytoremediation.[144] Some examples are provided below:

• The Green Lung is a phrase that can be used to describe situations where restored sites can become urban green space in and around crowded cities, allowing local people open space, a connection with nature, landscape and wellbeing and opportunities for exercise. Low input remediation processes can proceed in tandem with landscape improvement, and plants used in phytoremediation can themselves be part of the local landscape and ecology. A good masterplan for a Green Lung can include opportunities for sport and amenity (for example running, cycling, football, *etc.*), culture (for example meeting and performance spaces) and entrepreneurship (for example spaces for craft fairs, small scale catering such as café's *etc.*). This type of green infrastructure can be linked to larger scale functionalities such as wildlife pathways and opening pedestrian and cycle routes linking existing routes. The scale of a Green Lung application is variable. It may be small or large. It may also be a useful addition to build redevelopment on contaminated sites and brownfields, improving the "liveability" of these areas, improving their attractiveness to workers and providing opportunities for more sustainable buildings that make use of surrounding "soft" restoration areas for energy and water management. While the most obvious siting for a green lung is within urban areas, peri-urban and rural areas can offer opportunities where masterplans may be able to be developed over a far larger scale.

• Brownfields restored for green space provide opportunities for mitigation of conditions created in urban heat islands. Trees can provide shading respite for people (and animals) and the land area itself, depending on size offer opportunities for heat dispersion.

• Contaminated sites and brownfields operated as parks, ecological areas and similar using low input remediation can provide opportunities for sheltered employment of people, for example for maintenance or as care wardens. Sheltered employment is a setting in which people with disabilities receive services and training to develop work-related skills and behaviours.[145] In the UK this has created space for people with autism to find employment.[142] However, the possibilities are far wider, for example, creating places for the transition back to work of people with spent convictions, or problems of addiction. An interesting possibility is the development of allotments and gardens on brownfields, should risk assessment indicate this is an acceptable way forward.[146]

5 Discussion

There are competing demands for the land surface, in part exacerbated by the green transition, including food production, feedstock, renewables (such as solar arrays) and an unceasing demand for urban growth as populations become increasingly urbanised. In Europe a major challenge is urban encroachment on "greenfield" land. The EU has set a target of "no net land take" by 2050, meaning that the amount of land converted to artificial surfaces (like urban areas and infrastructure) should not exceed the amount of land reverting to natural or semi-natural uses. In these contexts of increasing land use pressures, a "circular economy for land" becomes a critical requirement, and the presence of underused or degraded sites such as brownfields, is an underexploited resource. Definitions may vary by region, but brownfields are commonly characterised by a history of soil disturbance, real or perceived contamination, and the need for remedial interventions to return them to beneficial use.[147] A European project from the early 2000s provided a useful classification of brownfield types, the "ABC Model".[147] This model sets that the economic feasibility of contaminated sites and brownfield redevelopment can be categorised as: type A sites whose development is immediately financially viable; type B sites where the economic case is borderline of profitability, where a public-private partnership to restoration may be needed; and Type C sites where restoration is not economically viable in a conventional way, given the site's conditions, its economic context and the perception of viable opportunities for future land. Type C sites can become long term brownfield, and in some cases also Type B. Action may be taken to deal with issues that are serious and urgent, but overall, the full reintegration of the brownfield land to a circular economy is stalled. LIRT offer particular opportunities for Type B and Type C site transition.

The most significant hurdle for LIRT is that, despite decades of research and demonstration experience, their practical deployment by contaminated site management practitioners remains limited. Given the financial drivers, it is understandable that the majority of remediation projects have focused on the rapid return of Type A sites to build redevelopment or rapid regulatory sign-off of formerly polluting industrial or manufacturing sites. Consequently, nature-based and other low-input practices have had relatively little market penetration to date as they are perceived to be slower, especially for source removal. However, these practices are often quite fast in terms of pathway management.[11]

On the other hand, their ability to deliver wider benefits additional to risk management creates opportunities for imaginative solutions to the problem of long-term brownfields, which are further enhanced by the relatively low cost of LIRT given their lower material and energy intensities. The necessary catalysts for achieving this are (a) regulatory acceptance of pathway management as a suitable risk management solution[148] and (b) the ability to understand, quantify and/or leverage the value of the wider benefit they can deliver.[21] These wider benefits include, but are not limited to, carbon storage, biodiversity gain, dual purposing such as for flood mitigation or renewables/biofeedstocks, and/or the creation of landscapes that support public amenity and more liveable urban spaces (including through provision of physical and mental health benefits). The societal benefit of these wider gains may provide very substantial leverage to bring "Type B" and "Type C" sites back into use, even after decades of stagnation. Exploiting this leverage depends on a convincing means of including societal benefits, and not just "business as usual" direct financial gains into value propositions. Such inclusion can be: (a) internalising societal benefits that are useful for private funders such as revenue from renewables or biodiversity offsetting, (b) valuing wider benefits for public funders for example gains in an area's "liveability", or (c) making wider benefits more explicit and persuasive in nonfinancial terms, for example, by using multi-criteria analysis to provide a political motivation for public investment.[21]

6 Conclusions

Low input remediation provides a useful opportunity to implement remediation on sites where economic circumstances are unfavourable or technically infeasible or where more conventional remediation approaches are too expensive or not technically feasible. This opportunity arises because low input remediation technologies may be more cost-effective, and because they may create wider opportunities for a greater range of possible beneficiaries. In many cases this opportunity requires a shift from preferring source management (which may take a long time using LIRTs) to pathway management (which can be more rapidly achieved), often combined with a repurposed land use, for instance for amenity, habitat or renewables or some combination.

LIRT can also provide multiple sustainability gains (for example reduced carbon impacts, reduced resource intensity). Sustainability gains are always very site specific, for example the context of the site's use, its location, its potential re-uses and the urgency with which remediation is necessary. However overall, LIRT, and potentially their linked re-use, can be very useful tools for sites where restoration has been stalled and for areas around built redevelopment that will become managed landscape.

The choice of using LIRT *versus* more resource and energy intensive technologies is not an "either-or" decision. Remedial approaches should be combined in an overall strategy that delivers the risk management goals required with the greatest overall net benefit. For instance, such a strategy may combine intensive techniques to deal with acute problems where there is a regulatory demand for source removal, with LIRT to manage residual source terms and pathway management.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Appendix

Biochar: a carbon-rich material produced from biomass through pyrolysis, used as a soil amendment to improve soil properties and immobilise contaminants.

Bioconversion: the biological conversion of contaminants into organic end-products.

Biolabile: readily biodegradable pollutants (such as petroleum hydrocarbons).

Dehalorespiration: a type of anaerobic respiration in which microorganisms remove chlorine atoms from chlorinated compounds, typically used in the remediation of chlorinated solvents.

Fixation: the process by which contaminants are chemically bound to a substrate, reducing their mobility and bioavailability.

Gentle remediation options (GRO): risk management techniques that provide a net gain (or at least no net loss) in beneficial environmental, social, and economic outcomes, often utilising plants, microbes, and fungi.

Humic materials: complex organic substances formed from the decomposition of plant and animal matter, contributing to soil structure and fertility.

In situ bioremediation: the use of biological processes to degrade or transform contaminants within the soil or groundwater.

Low-input remediation techniques (LIRT): remediation methods characterised by lower energy and resource demands, often leveraging natural processes, renewable resources, or energy sources to manage contamination.

Mineralisation: the complete conversion of organic contaminants into inorganic products.

Nature-based solutions (NBS): solutions that deploy natural processes across soil, air, water, and biology to protect, sustainably manage, and restore ecosystems in ways that address societal challenges and provide human well-being and biodiversity benefits.

Pathway management: remediation efforts focused on controlling the routes through which contaminants can reach receptors (*e.g.*, humans, ecosystems), rather than directly addressing the source of contamination.

Permeable reactive barrier (PRB): a subsurface barrier containing reactive materials that intercept and treat contaminated groundwater as it flows through.

Persistent organic pollutants (POPS): as set out in the Stockholm Convention: POPs are chemicals that remain intact in the environment for long periods, become widely distributed geographically, accumulate in fatty tissue of humans and wildlife, and have harmful impacts on human health or the environment.

Redox processes: chemical reactions involving the transfer of electrons between substances, leading to changes in oxidation states.

Risk-based land management (RBLM): an approach to managing contaminated land that focuses on assessing and mitigating the risks posed by contaminants to human health and the environment, allowing for reuse and redevelopment of sites.

Saturated zone: the area below the water table where all pores and fractures are filled with water.

Sorption: the process by which a substance becomes attached to another by physical or chemical forces.

Source control: remediation efforts focused on directly addressing and eliminating or reducing the source of contamination.

Sustainable remediation: remediation strategies that aim to maximize environmental, social, and economic benefits while minimizing negative impacts, aligning with sustainability goals.

Vadose zone: the unsaturated zone between the soil surface and the groundwater table.

Zero-valent iron (ZVI): elemental iron used as a reducing agent to degrade or immobilize contaminants in soil and water.

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