Sustainable remediation and redevelopment of brownfield sites

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Abstract

Anthropogenic activities have caused widespread land contamination, resulting in the degradation and loss of productive land, deterioration of ecological systems, and detrimental human health effects. To provide land critical for future sustainable development, remediation and redevelopment of the estimated 5 million global brownfield sites is thus needed. In this Review, we outline sustainable remediation strategies available for the cleanup of contaminated soil and groundwater at brownfield sites. Conventional remediation strategies, such as dig & haul and pump & treat, ignore externalities including secondary environmental burden and socioeconomic impacts such that their life cycle detrimental impact can exceed their benefit. However, a range of sustainable remediation technologies offer opportunities for urban revitalization, including sustainable immobilization, low-impact bioremediation, novel in-situ chemical treatment, and innovative passive barriers. These approaches can substantially reduce life cycle environmental footprints, increase the longevity of functional materials, alleviate potential toxic by-products, and maximize overall net benefits. Moreover, the integration of remediation and redevelopment through deployment of nature-based solutions and sustainable energy systems could render substantial social and economic benefits. While sustainable remediation will shape brownfield development for years to come, ethics and equality are almost never considered in assessment tools, and long-term resilience needs to be addressed.

1. Introduction

4.2 billion (55%) of the world's population currently live in urban areas, with that number expected to increase by 2.5 billion people before 2050 (ref [1]). This growth is happening at a time when the nature of urban economic activity is shifting; industrial sites that were once at the heart of industrialized urban centers are increasingly passing their economically productive lifespan and abandoned [2]. A vast number of these previously-developed sites stay derelict or underused due to urban planning controls or land use restrictions relating to the potential of soil and groundwater contamination by hazardous substances [3]. This so-called "brownfield" land (contrasting with undeveloped "greenfield" land) [2] is numerous. Using data from 35 countries and regions, we established a polynomial relationship between the number of sites per 1,000 population and per-capita GDP. Combining literature data and calculated results, we estimate that globally there are >5 million potentially contaminated sites (namely, brownfield sites) (Fig. 1).

These brownfield sites are associated with a variety of nuisances. Toxic heavy metals and volatile organic compounds (VOCs) are released from piled solid wastes, leaked pipelines, broken storage tanks, and wastewater ponds, causing the contamination of adjacent soil, water, and air, leading to visual and odor nuisances [6]. The contaminants further migrate in anisotropic, heterogeneous aquifers underneath the site, which further pose a hidden threat to human health due to groundwater pollution (as a drinking water source for urban dwellers) and vapor intrusion [7,8]. The brownfield sites are also associated with a variety of social and economic issues. Due to perceived risk associated with brownfield sites (Fig. 2a and 2b), nearby property value would be depreciated in comparison with market value and attract the poor [9]. Minority groups are more likely to live near contaminated sites, implying indirect discrimination and environmental injustice [10,11].

Land recycling of these numerous brownfield sites offer opportunities for land management [12]. The rapid increasing speed of global land take for settlement, which would double in 2050 as has been estimated by the United Nations [12], highlights the necessity for the reuse and revitalization of these derelict lands. Indeed, the adoption of the "no net land take by 2050" initiative by the European Commission implies that nearly all future urbanization in the EU will need to occur on brownfield sites [13]. While the benefits of brownfield remediation and redevelopment (BRR) are clear—including reduced human health risks, racial and health injustices, and crime and incivilities, as well as economic growth [9]—traditional BRR (Box 1) is often hindered by high cost, cumbersome administrative processes or uncertain remediation performance [14].

However, the emerging concept of sustainable remediation holds promise to accelerate BRR by minimizing adverse side effects and maximizing net benefits [15]. Sustainable remediation is drawing attention on account of three important factors: the recognition of the life cycle adverse impact of traditional remediation, institutional pressures exerted by new industrial norms, and stakeholder demand for sustainable practice [15], the latter driven by, and resonating with, the UN World Commission on Environment and Development [16] and the Sustainable Development Goals (SDGs) of the UN 2030 Agenda [17].

Yet, there are also concerns that businesses will use this concept for "green washing", claiming a remediation project or technology is sustainable without robust evidence [18], or to simply reduce project costs for liability owners by doing less remediation [19]. Thus, it is vital to better understand the holistic impacts of remediation and redevelopment so as to materialize the full potential of sustainable remediation practices.

In this Review, we outline sustainable strategies for brownfield remediation and redevelopment. We begin with a discussion of the primary, secondary and tertiary impacts of traditional practices over the life cycle of remediation. Then, we summarize promising sustainable strategies, namely, innovative in-situ soil and groundwater remediation technologies and strategies that integrate remediation with redevelopment. We end with identification of challenges and future research directions.

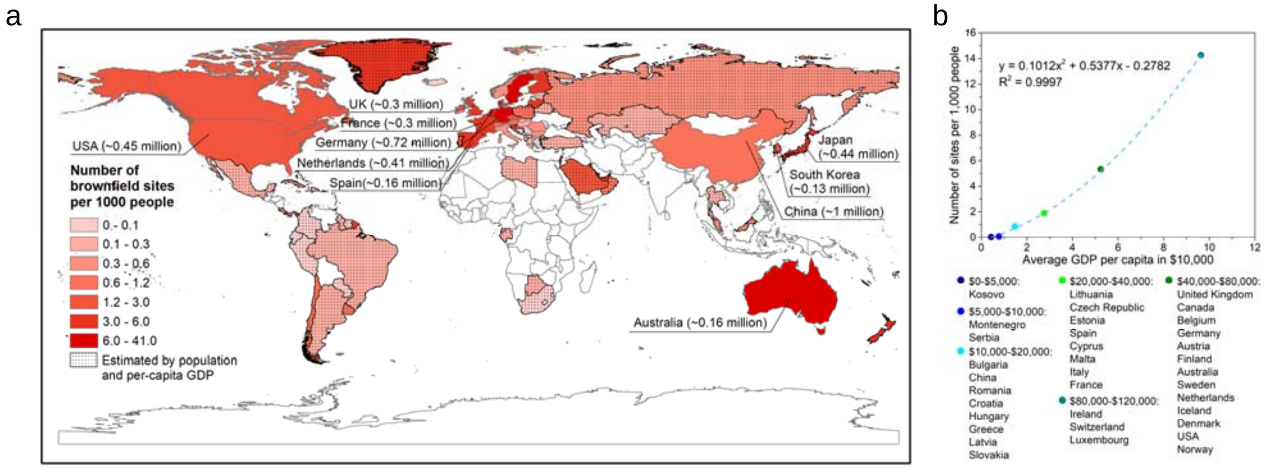


Fig. 1. Global number of brownfield sites: a| Country-level number of brownfield sites, with the top 10 countries labeled. The number of brownfield sites per 1,000 people is color coded, countries with literature data solid, and estimates for other countries derived using population and per-capita GDP data hatched. b| a polynomial relationship between sites per 1,000 population and per-capita GDP based on grouped average values [3-5,20,21]. The number of contaminated sites is estimated to exceed 5 million.

Box 1. Traditional brownfield remediation and redevelopment (BRR) strategies.

Dig & Haul, also known as excavation and off-site disposal, is the most widely used BRR strategy due to its simplicity of operation. It involves the excavation of contaminated soil, transport, and off-site disposal. Pre-treatment is necessary sometimes to meet disposal requirements [24,25]. Dig & haul involves the transportation of a large quantity of contaminated soil through populated areas. It also faces the problem of long-term landfill operation, potential leakage and associated liability.

Pump & Treat is a groundwater remediation strategy, which includes retrieval of contaminated groundwater using extraction wells, or trenches, cleanup in above ground treatment system (either on-site or off-site), and final discharge of treated water. This technology was traditionally designed for contaminant mass removal, but often with long operation periods, sometimes up to several decades, due to diminishing efficiency associated with back diffusion from aquifer matrix. Nowadays it is more often designed to manage plume migration [26,27].

Thermal desorption refers to the process where soil contaminated by volatile contaminants is heated at a temperature typically ranging from 90 to 560 °C, so that these contaminants can be physically separated from the soil matrix, and treated with an off-gas treatment system [30,31]. This thermal treatment technology is highly energy intensive, rendering a high carbon footprint.

Chemical treatment makes use of oxidation and reduction agents for the remediation of organic contaminants or hexavalent chromium in contaminated soil or groundwater. It can be conducted either ex-situ (mixing soil with agents following excavation) or in-situ (injection of agents to vadose zone or groundwater). Typical oxidation agents include ozone, peroxide, permanganate, persulfate, while reduction agents include zero-valent iron (ZVI), ferrous iron, polysulfides, and sodium dithionite [22,23]. The manufacturing of these reagents often renders high environmental footprint, and in some case their application also results in toxic byproducts.

Solidification/Stabilization (S/S) is a soil remediation strategy, where contaminated soil is mixed with binding agents either in-situ or ex-situ [28,29]. The contaminated soil is physically bound and enclosed within a solidified matrix (solidification), or chemically reacted and immobilized by the stabilizing agent (stabilization). Labile forms of contaminants are immobilized into less-labile forms during this process, thus rendering lower leachability. Cement is the most widely used S/S agents, but it also renders high environmental footprint.

2. Life cycle impact of brownfield remediation and redevelopment

Traditionally, brownfield remediation was considered as "inherently sustainable" because it involves removing toxic chemicals from the environment, frees up contaminated land for reuse, and reduces urban sprawl. However, many environmental and socioeconomic externalities associated with remediation activities have been uncovered based on holistic sustainability assessment (Fig. 2). In sustainable remediation terminology, the type of impact can be divided into primary, secondary, and tertiary impacts (Box 2) based on their relationship to site boundary and site use. Life cycle based approaches have often been used to compare various technologies and identify the most sustainable strategy, as well to recognize impact hot spots and identify opportunities for optimization by sensitivity and scenario analyses. This section discusses various aspects of life cycle impact of traditional BRR practices. Note that assessment frameworks, such as life cycle primary-tertiary impacts (Box 2), also apply for sustainable BRR strategies to be discussed in Section 3.

2.1 Environmental impact

Development on brownfield land with contaminated soil and groundwater can have serious environmental consequences. For example, a former chemical dumpsite in New York, USA was developed for residential housing and schooling. Exposure to toxic substances in the soil and groundwater increased chromosomal damage among local residents by over 30 times [32]. Therefore, remediation is often required pre-redevelopment in order to mitigate the environmental risk, rendering substantial health benefits for local neighborhoods. Aggregated analysis of a large number of sites has shown that remediation can reduce the chance of children living within 2-km lead contaminated sites having elevated blood lead levels (BLL) by 13~26% (ref [33]), leading to a 20~25% reduction in infant congenital anomalies within 2-km of remediated superfund sites [34]. On the other hand, cleanup activities are associated with significant detrimental environmental impacts themselves. A sustainability assessment of the remediation of a single brownfield site in New Jersey, USA, calculated the potential to emit 2.7 million tons of CO_2 if a dig & haul - the most widely used traditional remediation approach [35] - was implemented at the site. This figure is equivalent to 2% of the annual CO_2 emissions for the entire state [15,36].

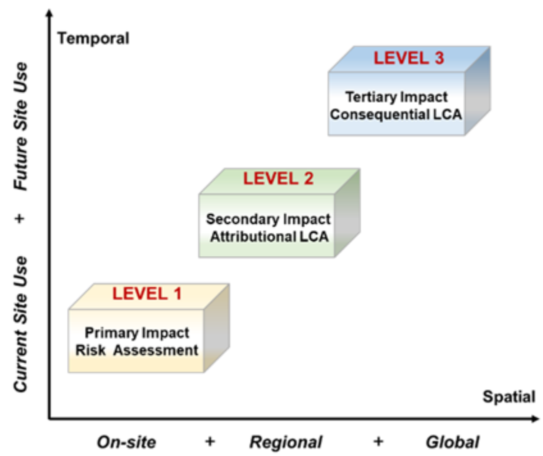
The environmental impact of brownfield remediation can extend well beyond the spatial boundary of the site or even local communities [37]. The impacts are associated with upstream processes like off-site fossil fuel burning as an energy source and the acquisition of remediation materials, and downstream processes like off-site hazardous waste disposal and long-term maintenance, in addition to the on-site remediation activities like soil excavation, groundwater extraction, and in-situ chemical oxidation [38]. Environmental impact assessments have tended to include three major categories: ecology, human health, and resource, but the specific impact indicators are more diverse, with global warming, human toxicity, and eco-toxicity potentials often being the most notable indicators [38]. Studies have shown that the sum of the detrimental environmental impact of remediation can exceed that of no-action being taken, posing doubt on the legitimacy of conducting aggressive remedial actions (Box 2). Due to the recognition of detrimental environmental impacts during remediation, the USEPA is actively promoting green remediation as a way to minimize the life cycle environmental footprint [39], while European practitioners seek sustainability assessment to maximize the net benefit of remediation [40].

The state of brownfield being derelict and the duration of remediation also renders implications to life cycle environmental impact. Slow pace in brownfield remediation and redevelopment means that new urban development would occur on greenfield. Greenfield sealing jeopardizes its socio-ecological functions in supplying groundwater, producing oxygen, regulating micro-climates, and providing recreational value [14]. In this perspective, more rapid remediation technologies, like dig & haul and thermal desorption, provide a positive environmental value. Life cycle impact assessment (LCIA) that incorporates land resource as a midpoint indicator may be used to capture this intangible benefit [41]. Alternatively, the environmental impact can be captured by expanding the system boundary to include the substitution of brownfield redevelopment with greenfield development. A city-level assessment using this approach found that brownfield redevelopment compared to greenfield development in the San Francisco Bay Area of California, USA, could reduce greenhouse gas emission by 14% over a 70-year period [42]. This is because it would significantly reduce commute distances, cut back energy demand for space cooling and heating, as well as requiring less new road and utility infrastructure [43]. In order to fully capture the extended environmental impacts, it is also essential to consider a wide range of social impacts associated with brownfields.

Box 2. Primary, secondary, and tertiary impacts of brownfield remediation

Traditional decision-making for brownfield site remedy mainly focuses on the site itself. However, evidence has shown that impacts of a remedy go beyond the site spatial and temporal boundaries, affecting a larger scale and a longer time series. Hence a holistic view that goes beyond site boundary and looks beyond the contemporary time horizon should be required. In sustainable remediation typology,

- Primary impact refers to those caused by the toxic substances initially present in environmental media at a brownfield site, including contaminated soil, groundwater, and sediment [44].
  - Typical primary impact includes carcinogenic and non-carcinogenic human toxicity from oral, dermal, or inhalation exposure, eco-toxicity due to plant uptake or bioaccumulation in food webs.
  - Primary impact is quantified using long-term monitoring data or predictions based on contaminant fate and transport modeling [45]. The quantification of primary impact is critical in comparing remedial alternatives [46]; however, most existing remediation LCA studies lack its inclusion, which can result in misleading conclusions [47].



- Secondary impact refers to those associated with the remediation activities [45].
  - They can include all pertaining cradle-to-grave processes, such as the environmental footprint of electricity generation, equipment manufacturing, and remediation reagent synthesis [48]. Researchers have used various system boundaries to exclude some minor processes or common processes that do not directly relate to a decision regarding remediation choices [37]. Secondary impact is included in most remediation sustainability assessments, often using the LCA method.
  - The comparison of primary impact and secondary impact can decide whether remediation renders net environmental benefit [47]. For example, the remediation of a trichloroethene contaminated site in Denmark using thermal desorption or dig & haul methods could increase the carcinogenic human toxicity by 2 times and 7.6 times, respectively, implying both strategies were less desirable than taking no action from the human toxicity perspective [45].
- Tertiary impact refers to those associated with post-remediation brownfield site usage [49].
  - While both primary and secondary impacts are attributional, namely, reflecting the average environmental burden associated with completing a functional unit of remediation service [45], tertiary impact is consequential, that is, reflecting how various brownfield remediation options affect environmental relevant flows to and from the site during the post-remediation phase [50].
  - Tertiary impact has drawn much less attention than primary and secondary impacts in sustainability assessment studies. It was first conceptualized in a LCA of BRR in Montreal urban core, Canada [49]. Follow-up LCAs have shown that tertiary impact can well exceed primary and secondary impacts in magnitude [37], which suggests that the integration of remediation and redevelopment could greatly benefit sustainable remediation, because tertiary impact is mainly dependent on redevelopment strategies.

2.2 Social impact

Brownfield sites are often disconnected from the local urban context and represent a social stigma [51]. Brownfield remediation and redevelopment can bring a range of social benefits, including the revitalization of deprived urban community, supplying new jobs, providing new housing, improved public health, and reducing urban sprawl [52]. But remediation activities can render negative social impact in themselves. For example, remediation workers might lack sufficient awareness and protection against potential hazards at brownfields [53]. Remediation operation can also cause serious secondary pollution and affect the local community. In Changzhou, China, remediation operation at a former chemical plant site caused pungent smell at an adjacent middle school, and hundreds of students attributed their abnormal health condition to secondary pollution from the remediation project [54].

Social impact is generally underrepresented in sustainable remediation literature [36,52]. Newly developed sustainability assessment frameworks and tools are starting to include more social impact indicators [55]; however, they are still very limited in comparison with environmental impact. A literature review of thirteen sustainability assessment tools found that human health and safety was the only social criterion included in all tools [56]. In contrast, ethics and equality are almost never considered in the assessment tools, even though this impact category is considered highly relevant to brownfield remediation [40,57]. Moreover, the assessment of social impact is usually subjective in existing appraisal tools [41], making it difficult to systematically use in decision making.

Brownfield remediation and redevelopment requires concerted intervention from various stakeholders in order to properly take the various social impacts into account [14]. Greenfield development is more attractive to land developers because there are less uncertainties and project schedule is more controllable [58]. Due to the direct and indirect social impact associated with brownfield, the economic value of land is often discounted, which can persist even after remediation is conducted [59]. Therefore, the revival of brownfield sites requires a broad recognition of the social benefits and to put them in the context of economic development.

2.3 Economic impact

The economic impact of brownfield remediation consists of both direct and indirect economic impacts. The direct impact mainly entails the financial cost of carrying out remediation projects including both short-term capital cost and long-term maintenance cost [60], as well as the financial return from selling or redeveloping a brownfield site and pertaining "opportunity cost" [61] (Fig. 2). The investment return depends on the choices of remediation and redevelopment strategies (Fig. 2c and 2d). This has been a cornerstone of traditional decision making in prioritizing remediation among a large portfolio of brownfields [62]. At brownfield sites that are financially non-profitable, public funding or other incentives are required to promote BRR [63], for which the indirect economic impact derived from environmental and social benefits must be accounted for.

Brownfield remediation and redevelopment can reduce health care cost associated with contamination exposure, attract public and private investment, improve employment and local tax revenue, lower crime rates and associated law enforcement costs [64]. Contingent valuation analysis at a brownfield site in Athens, Greece, showed that local residents were willing to pay 0.23% to 0.44% of their income for environmental cleanup alternatives [65]. The economic impact of BRR is also reflected in the local housing market. A hedonic pricing model showed that brownfield cleanup in the US can increase the value of properties within a 5-km radius by 5% to 11.5% (ref [9]). The cleanup of hazardous waste sites was found to increase nearby property values by 18.7~24.4% (ref [66]). Due to the increase of property value, local tax revenue near 48 remediated brownfield sites was estimated to increase by \$29 to \$73 million per year, which was 2~6 times that of USEPA's spending on the cleanup of those sites [67]. BRR allows new businesses to emerge and draw new employment on redeveloped sites, for instance, 246,000 new jobs created on 650 remediated Superfund sites in the US [68]. Besides these tangible benefits, cost-benefit analysis (CBA) can account for a wider range of environmental and social impacts using monetary terms over a longer time horizon [69].

The direct and in-direct economic impacts of remediation often spilt in opposite directions: the former as a cost on the liability owner or land developer and the latter as a benefit to the greater society. They can be reconciled by stakeholder engagement involving local government, site owners, land redevelopers, future site users, and the local community [70]. However, in reality, BRR is often hindered due to imperfect information, the financial burden associated with uncertain project duration, and liability concerns [71]. Moreover, decision making tools, like CBA, encompass a broad range of costs and benefits, which are not universally accepted by all stakeholders [59]. Existing published studies have often focused on specific case study sites, rendering difficulties in transferring these results to metropolitan or regional level decision making [71]. Some important value considerations may be non-quantifiable due to lack of data. For instance, the economic value of brownfield ecosystem services are largely an unknown [71]. Therefore, their usefulness in evaluating soft reuse strategies like nature based solutions (NBS) maybe limited or even controversial [72]. Future quantitative economic assessment tools will need to address these challenges by providing more transparent, standardized, and, importantly, justified monetization parameters and assumptions.

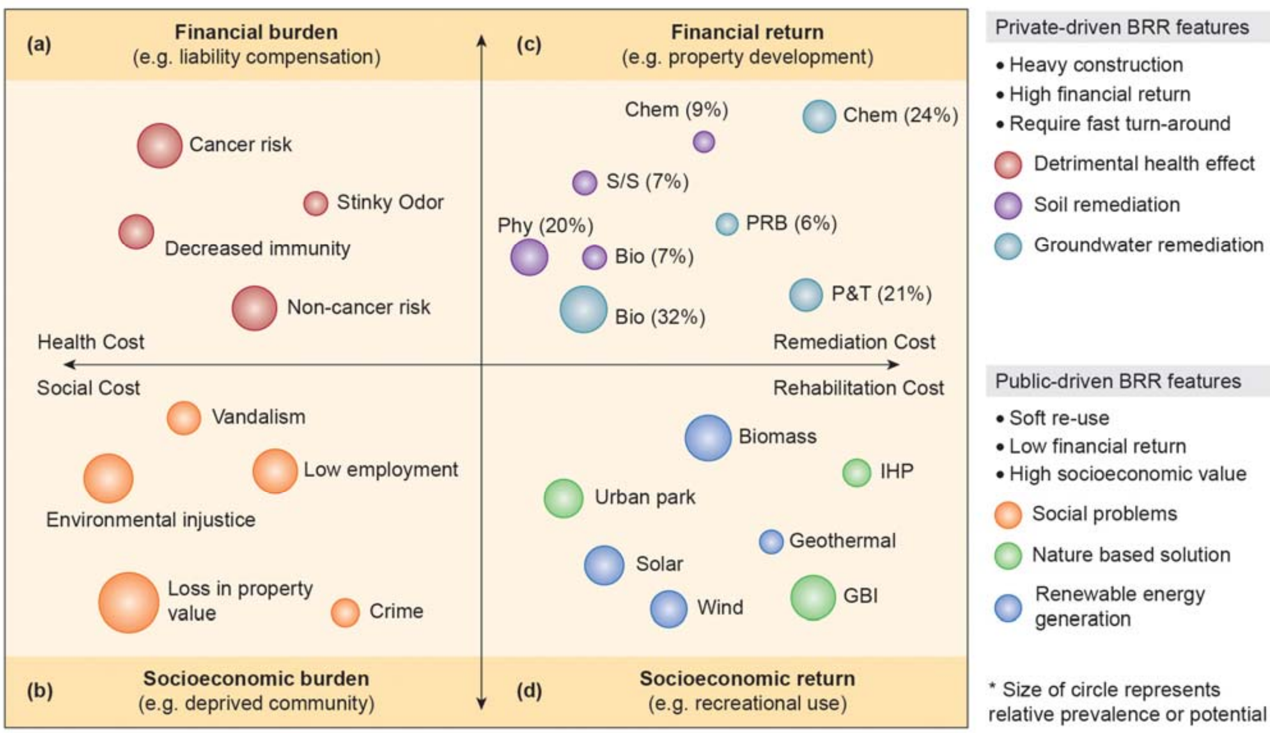


Fig. 2. Social and economic impact comparisons of brownfield remediation and redevelopment strategies. a| Health cost associated with contamination at brownfield sites [73-76]. The x axis represents the health cost, while the y axis represents the financial burden. Larger circle represents higher relative prevalence of a certain issue (qualitative). b| Social problems of derelict brownfield sites [10,51,77]. The x axis represents the social cost, while the y axis represents the socioeconomic burden. Larger circle represents higher relative prevalence of a certain issue (qualitative). c| Remediation cost versus financial return of various treatment technologies, percentage of market share based on US Superfund data in 2013~2017 (ref [35,78]). The x axis represents the remediation cost, while the y axis represents the financial return. Larger circle represents the percentage of market share (quantitative). d| Rehabilitation cost versus socioeconomic return of various BRR integration strategies [59,79-81]. The x axis represents the rehabilitation cost, while the y axis represents the socioeconomic return. Larger circle represents higher potential for the rehabilitation return (qualitative). Bio=bioremediation; BRR=brownfield remediation & redevelopment; Chem=chemical treatment; GBI=green and blue infrastructures; IHP=industrial heritage park; Phy=physical separation; P&T=pump & treat; PRB=permeable reactive barrier; S/S=solidification/stabilization. These social and economic burdens and returns are crucial factors that should be considered to judge whether a BRR is sustainable.

3. Sustainable remediation technologies

Considering the significant environmental, social, and economic impacts associated with traditional remediation strategies, technological innovation is required to maximize the sustainability potential of remediation. A number of novel, sustainable remediation technologies have emerged, including sustainable immobilization that uses novel binding agents with low carbon footprint to achieve contaminant passivation, low-impact bioremediation that uses plants and/or microorganisms to extract, stabilize, or degrade contaminants, novel in-situ chemical treatment that uses nanomaterials to achieve long-term effectiveness, innovative passive barrier system that incorporates novel filler materials with high selectivity, bio-electrokinetic remediation that uses microbial fuel cells (MFCs) for contaminant removal, low-impact soil washing that uses biodegradable chelating agents to enhance contaminant desorption from soil solid particles, and low-temperature thermal desorption that reduces energy consumption for contaminant volatilization. In this section, the first four sustainable remediation technologies that hold promise in maximizing the net benefit of brownfield remediation are discussed. These four technologies were selected primarily on the basis of technology maturity, and secondarily based on the results from previous life cycle assessments that compared the environmental, social, and economic impacts of different methods in specific cases. It should be noted that the net benefit and sustainability of any specific technology will be dependent upon site specific characteristics, and alternative technologies that are not discussed here may be more sustainable under certain site conditions.

3.1 Sustainable immobilization.

Sustainable immobilization represents an evolution from the traditional remediation approach of solidification/stabilization (S/S) of contaminated soil. The S/S method has been used for many years as an effective and relatively cheap way to immobilize heavy metal contaminants within the soil matrix (Box 1, Supplementary Fig. 1) [82]. However, the solidification part of S/S usually relies upon the introduction of Portland cement (PC) into contaminated soil, which renders a high carbon footprint (Supplementary Table 1), with cement manufacturing being the 3rd largest anthropogenic source of CO_2 emissions [83]. Hence the key to sustainable solidification is to lower the environmental impact by replacing Portland cement into greener and alternative cementitious binders. A wide varieties of novel binders have been developed, such as cement free clay-based binders, and alkali activated fly ash/slag (such as geopolymer) [84,85]. Apart from this environmental benefit, these natural or industrial waste-derived, cement-free alternatives also exhibit high economic viability for large-scale soil remediation with a comparable or even reduced cost compared with Portland cement [86].

Sustainable solidification also involves recycling of properly treated soil. Such re-use strategies avoid the high energy costs associated with off-site transportation and landfilling and offset the economic cost and environmental burden of long-haul importation of raw construction materials [87]. For instance, strongly solidified contaminated soil with high mechanical strength can be reused as artificial aggregate for roadway subgrade [88]. A case study showed that one such treatment and re-use scenario reduced the life cycle greenhouse gas emissions by more than a third (35%), and reduced life cycle human toxicity impact by nearly two thirds (65%) in comparison with dig & haul remediation. Moreover, if fly-ash based green cement is used to replace Portland cement, the average life cycle environmental impact could be further reduced by 40% (ref [88]).

The stabilization part of S/S mainly uses lime, phosphate, and other alkaline materials for the chemical sorption and precipitation of contaminants within the soil matrix without improving soil's mechanical strength [89]. Therefore, the stabilized soil can be reused for plant growth. However, soils treated by these conventional stabilization agents may suffer from degraded soil health, productivity, and biodiversity due to high disturbance to the physicochemical properties such as aggregation and water penetration [90], and decreased carbon stability [91]. The overuse of phosphate for soil amendment also causes an irreversible loss of terrestrial phosphorus stock [92].

A series of novel stabilization materials have been proposed, including layered double hydroxides (LDHs) [93] and biochar composites [94]. Biochar is particularly promising for sustainable stabilization because it offers lower life cycle environmental impact from different aspects (Supplementary Table 1). Firstly, it is a waste-derived biosorbent that immobilizes a wide range of pollutants, both organic and inorganic, via its porous structure, large surface area, and abundant functional groups [95]. Moreover, biochar is carbon negative, which is because the carbon content of biochar can be highly stable, with reported half-lives ($t_{1/2}$) of >1000 years, thus offering high potential for in-ground carbon sequestration [96] (Fig. 3a). Furthermore, biochar can concurrently improve soil health due to enhancing effects on soil fertility, aggregate stability, and soil organic matter [97]. Apart from soil carbon sequestration, biochar also improves other ecosystem services including reduced nitrogen leaching, reduced surface runoff, increased soil biodiversity, and enhanced water availability [98]. Social acceptance of biochar's promise as a soil amendment has also increased much, in particular for developing countries like China and India [99,100]. To assure the economic sustainability, biomass recovery and biochar pyrolysis systems should be established in a closed-loop manner [101].

Sustainable immobilization still bears the common problem of all immobilization techniques, in that contaminant substances are entrained within the treated material, in this case artificial aggregate, which means that long-term risk needs to be properly monitored and managed using science-informed guidelines and standard protocols. When applying re-use strategies, it should be aware that some practitioners may exploit the circular economy principle and unintentionally spread contaminants to a larger space to be dealt with by the next generation [102].

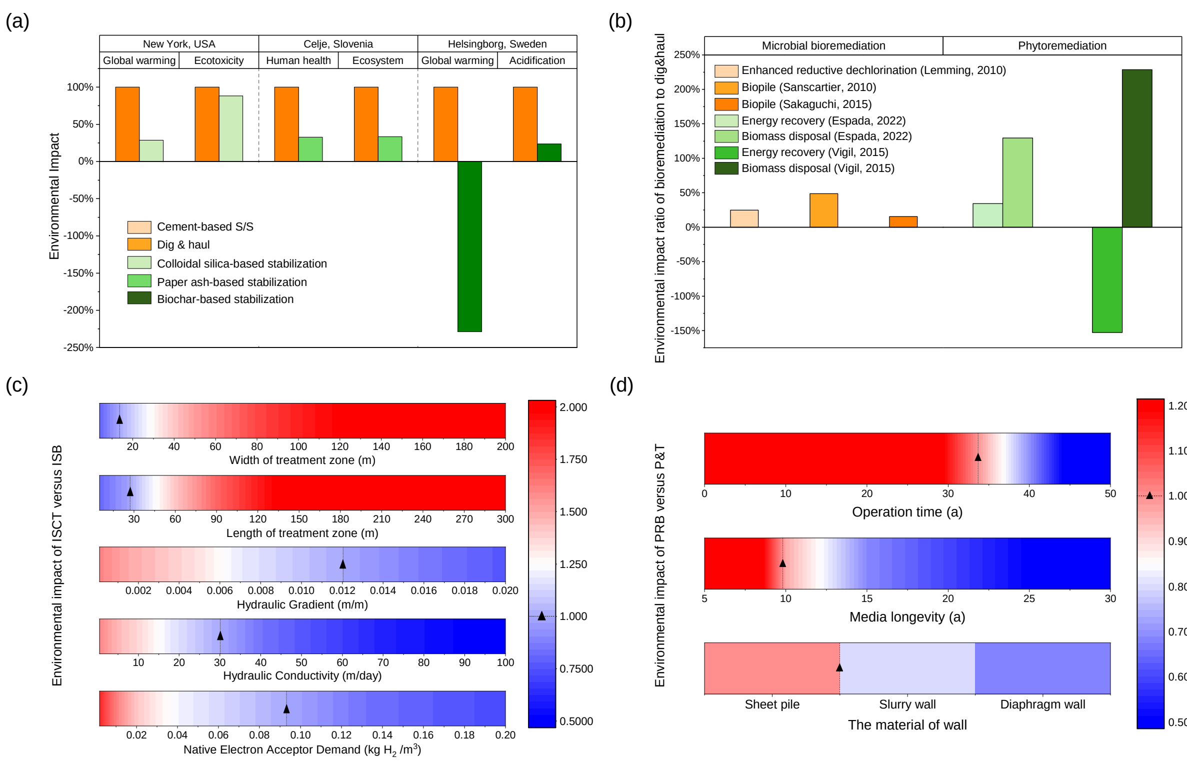


Fig. 3. Comparing the life cycle environmental impact between sustainable and traditional remediation technologies: a| the environmental impact of sustainable immobilization in comparison with dig & haul and conventional cement-based S/S, values were obtained via life cycle impact assessment for specific cases in New York, USA [103], Helsingborg, Sweden [104], and Celje, Slovenia [105]. b| the environmental impact of microbial bioremediation or phytoremediation in comparison with that of dig & haul in specific cases, values were calculated via life cycle impact assessment of five cases [45,106-109]; c| the environmental impact of in-situ chemical treatment (ISCT) in comparison with in-situ bioremediation (ISB) under a range of site characteristics, including width of treatment zone, length of treatment zone, hydraulic gradient, hydraulic conductivity, and native electron acceptor demand [110]; d| the environmental impact of permeable reactive barrier in comparison with pump & treat under different operation time, media longevity, and wall material compositions [111,112].

Sustainable remediation technologies render significantly lower life cycle environmental impact than traditional remediation technologies

3.2 Low-impact bioremediation.

Bioremediation is a green remediation approach that relies upon the ability of certain living organisms, including species of plants, bacteria, fungi, or soil animals, to remove contaminants in soil or groundwater. In this section phytoremediation that uses plants to remove or stabilize contaminants, and microbial bioremediation that uses microorganisms to degrade contaminants are discussed (Supplementary Fig. 1, Supplementary Table 1).

Phytoremediation is a widely explored soil remediation technique involving the use of plants to extract (phytoextraction), stabilize (phytostabilization), degrade (phytodegradation and rhizoremediation), or volatilize (phytovolatilization) contaminants [113]. A major benefit of phytoremediation is that it improves the ecosystem service of the originally degraded soil. Roots of plants used for phytoremediation prevents soil erosion and promotes aggregation [114]. Exudates of plants further stimulate the growth of microbes including plant-growth promoting bacteria (PGPB), thus achieving higher remediation efficiency, while simultaneously increasing soil biodiversity [115].

Among these techniques, phytoextraction has been extensively used as a gentle remediation option (GPO) for the remediation of slightly to moderately polluted agricultural soil systems [116]. For higher levels of contamination encountered at brownfield sites, the addition of mobilizing reagents to the contaminated soil may enhance phytoremediation performance [117]. More efficient phytoremediation technologies are under development based on new molecular mechanisms of plant-specific detoxification pathways and genetic modification [118,119]. It is notable that the bioremediation effect of plants is limited within the rhizosphere, which also makes it hard to use plants alone to remediate brownfields whose contaminants usually reach much deeper. Instead, phytoextraction can be used as a “polishing step” with high social acceptance due to improved aesthetics and created greenspace for leisure and entertainment, thus combining remediation with redevelopment in a natural manner [120]. Another promising technique is phytostabilization, which uses the specific metabolites from roots and/or rhizosphere microorganisms to decrease the solubility and mobility of contaminants [121]. Although this approach only reduces the mobility of contaminants without necessarily removing them, it does not generate contaminated secondary waste that needs further treatment [121]. It is suited for the remediation of large brownfields which are mildly contaminated by heavy metals [113]. Nevertheless, the long-term effectiveness of this technique should be further examined [113].

In-situ microbial bioremediation has also drawn wide attention, particularly for the remediation of groundwater contaminated by chlorinated solvents [122]. Microbial bioremediation of groundwater has the advantage of addressing the “back diffusion” problem better than traditional groundwater remediation techniques such as pump & treat [123] (Supplementary Table 1), which is a problem that has resulted in rebound, tailing, and ultimately the failure of many traditional remedial systems [124]. Researchers are also exploring innovative microbial bioremediation methods to treat recalcitrant and emerging pollutants such as PFOA/PFOS and antibiotics [125,126], as well as to enhance treatment efficiency for inhibitory comingled pollutants [127]. The rate of microbial biodegradation of pollutants is often limited due to low microbial quantity and activity, insufficient nutrients, and the oxidation-reduction potential (ORP) of the subsurface environment, amongst other factors. In this situation, bioremediation is usually enhanced by biostimulation and bioaugmentation. In biostimulation, the incorporation of certain amendments will stimulate naturally existing microorganisms to biodegrade pollutants at a faster rate. For example, injecting substrates, like vegetable oil, into groundwater provides a slow release of electron donors that render a favorable ORP condition and, thus, enables effective enhanced biodegradation over a long period [128]. Activated carbon also can be injected into the subsurface in order to retain chlorinated solvents for enhanced biodegradation [129]. In bioaugmentation, exogenous degrading microbial communities known to be effective for degrading certain types of contaminant are introduced to enrich the biodegradation potential of the microbial taxa within the contaminated groundwater, thereby accelerating the biodegradation process.

The sustainability of phytoremediation and microbial bioremediation lie in the high economic viability (Fig. 2c), high social acceptance, and low life cycle environmental impact. As an in-situ remediation method bioremediation offers a lower economic burden in comparison with most other traditional ex-situ remediation methods (Fig. 2c) [130]. Surveys have also shown that the general public perceive bioremediation to be more environmentally friendly and, therefore, it has high social acceptance [131]. The life cycle environmental impact of bioremediation is usually much lower than that of physical or chemical treatment methods. For example, LCA studies have shown that microbial bioremediation reduced global warming potential by 50%~90% in comparison with dig & haul remediation; and phytoremediation reduced environmental impact by up to 250% (Fig. 3b). A case study in Denmark revealed that in-situ bioremediation was the only remedial option that could out-perform the no-action option, with life cycle carcinogenic human toxicity impact 76% lower than thermal desorption and 92% lower than dig & haul [45].

However, both phytoremediation and microbial bioremediation still face various challenges, especially related to the long time taken to achieve remediation goals. For phytoremediation, it can render higher carbon footprints and overall environmental footprints than other approaches without energy recovery (Fig. 3b) [108,109]. A proper disposal of harvested biomass enriched with toxic elements is also required to assure the environmental sustainability (Fig. 3b), which may be costly [132]. The combination of phytoremediation with redevelopment, such as nature-based solution or sustainable energy harvesting, renders a promising direction (see next section). Microbial bioremediation is widely used in the US, but it has seen extremely low adoption rates in many countries, such as China, where the remediation market is development driven and requires faster-paced methods [102]. Moreover, bioremediation can potentially generate toxic by-products. For instance, reductive dechlorination of chlorinated ethene (such as TCE and PCE) involves the toxic substance vinyl chloride as an intermediary daughter product [122]. Therefore, it is important to develop specialized bioremediation treatment cultures, sequential treatment strategies, and complete biodegradation pathways toward non-toxic end products and at a rapid pace and controllable manner [133].

3.3 Novel in-situ chemical treatment.

In-situ chemical treatment of contaminated groundwater involves either in-situ chemical oxidation (ISCO) or in-situ chemical reduction (ISCR). Because in-situ treatment does not involve excavation, it tends to be more cost effective than pump & treat approach and is less likely to create unintended exposure scenarios or create dust and odor nuisance for local residents (Supplementary Fig. 1). In-situ chemical treatment has become one of the most widely used in-situ remediation approaches [35] because it can render more rapid cleanup times than other in-situ technologies.

However, evidence is mounting that traditional in-situ chemical treatment strategies could possess higher environmental impacts. The manufacture of chemical treatment reactants can cause substantial secondary environmental impacts beyond the site boundary [44,134]. When comparing the life cycle global warming potential for a diesel-contaminated groundwater remediation project, ISCO was found to render much higher impact than alternative technologies pump & treat and bio-sparging [44]. Moreover, ISCO needs to be applied with caution because it can lead to potentially severe secondary water quality issues, thus increasing the overall environmental impact. For example, it can cause the conversion of Cr(III) to highly toxic Cr(VI), and formation of manganese dioxide precipitates that clog aquifer pore space [22]. Nevertheless, under certain specific site characteristics, in-situ chemical treatment can provide lower environmental impact than other technologies [110], particularly at sites with relatively small contaminant source zones and a relatively large hydraulic gradient or hydraulic conductivity, or abundant native electron acceptors for chlorinated solvent sites (Fig. 3c).

Scientific advances are needed to render in-situ chemical treatment more effective and sustainable. Firstly, remediation materials must have greater treatment efficiency so that a smaller amount of materials need to be fabricated for a brownfield remedy, thus achieving lower environmental and economic impacts simultaneously. It can be accomplished via the adoption of decorated nanomaterials with high selectivity towards target contaminants. For example, the commercialization of nanoscale zero-valent iron (nZVI) has significantly advanced the efficiency of chlorinated solvent removal compared to traditional granulated ZVI [135]. The benefit are still being realized showing that nZVI renders high treatment efficiency for residual non-aqueous liquid (NAPL) via both in-situ abiotic degradation and pore-scale remobilization induced by gaseous products [136]. The nZVI technology has been advanced further by sulfidization, which provides both rapid dechlorination and defluorination of recalcitrant and emerging pollutants [137]. The addition of sulfur facilitates chemical reduction by atomic hydrogen and hinders hydrogen recombination. It renders treatments that are contaminant-specific, selective against the background reaction of water reduction and, overall, more efficient [138]. For example, FeS-coated nZVI has been shown to degrade trichloroethene 60 times faster than ZVI [139].

Secondly, innovative material design and material delivery need to be developed to maintain long-term treatment efficiency while avoiding or reducing secondary water quality issues. In this way the problem of back diffusion could be effectively mitigated (Supplementary Table 1). For example, sulfurized nZVI stabilized with carboxymethyl cellulose (CMC) can effectively treat a mixture of chlorinated solvents without accumulation of toxic byproducts [140]. Thermally activated peroxydisulfate ISCO helps desorption/dissolution of organic contaminants and efficient activation of oxidants, but has suffered from short lifetime of peroxydisulfate. Peroxide stabilizers have been developed that increase the longevity of thermally activated peroxydisulfate for enhanced ISCO remediation [141]. Controlled release mechanisms have also been explored as a way to offer long-term treatment of contaminated groundwater and avoid rebound issues [142].

Thirdly, green synthesis approaches need to be developed to produce in-situ chemical treatment reactant in a more environmentally friendly way [143]. Utilization of safer chemicals and solvents and maximization of atom economy, which are principles of green chemistry, serve as the key to lower the cradle-to-gate environmental footprint of material manufacturing [144]. Materials derived from biological waste hold great promise in this research direction [145].

3.4 Innovative passive barrier systems.

Complex hydrogeological conditions encountered at some brownfield sites make it infeasible to reduce pollutant concentrations in groundwater to risk-based target levels within a reasonable time frame [6]. It is therefore necessary to manage the risk by controlling the migration of contaminants. Permeable reactive barrier (PRB) systems rely on in-ground impermeable barriers to direct contaminated groundwater to flow through a permeable reactive zone, which removes contaminants by adsorption, precipitation, or degradation (Supplementary Table 1) [146]. The long-term effectiveness of PRB systems assure its environmental sustainability (Fig. 3d). For instance, for PRB systems based on adsorption using granular activated carbon (GAC), PRBs offer lower global warming impact than pump & treat if the operation time is relatively long and constructed without steel sheet piles (Fig. 3d) [111]. For a PRB system based on degradation by ZVI, PRB renders lower global warming impact than pump & treat as long as ZVI longevity exceeds 10 years [112] (Fig. 3d). The life cycle environmental impact of PRB systems is influenced by groundwater constituents, such as dissolved organic matter, due to their interaction with reactive media causing surface passivation and flow path blockage [147]. A retrospective assessment on one of the earliest installed PRB systems indicated that ZVI had remained biogeochemically active for over 20 years [148], suggesting that passive barriers can be effective for long-term risk management.

The future development of PRB systems lies in novel functional materials and processes that render enhanced removal efficiency, high selectivity, and extended longevity. In this context both environmental and economic sustainability can be improved. Such materials and processes should be carefully designed to exploit multiple and complementary functionalities. For example, an innovative nanomaterial was developed for use in barrier systems using chemically modified lignocellulosic biomass, achieving high adsorption capacity due to their amphiphilic properties, while enabling subsequent fungal-based biodegradation of PFOA/PFOS contaminants [149]. This newly designed material renders a 97% reduction in net CO_2 emission compared to GAC-based treatment. The affinity of pyridinium-based anion nanotraps was manipulated to enable long-term segregation of radionuclide contamination under extreme acidic and basic conditions [150]. In another case, an in-situ ultrasonic reactor was established as an innovative passive barrier, which could reduce CO_2 emission by 91%

over a 30-year period in comparison with pump & treat of PFAS contaminated groundwater [151]. These innovative materials and processes have potential in creating a new generation of PRB that significantly increases the overall net benefit of remediation.

A common theme of the four sustainable remediation strategies discussed above is technological innovation which reduces material and energy input, as well as minimizing waste and secondary toxic byproducts, while enhancing economic vitality and social acceptance. Traditional remediation agents are replaced with waste-derived, green-synthesized, or natural materials, or living organisms, thus lowering the life cycle environmental impacts and economic costs associated with material fabrication. Moreover, gentle remediation options also improve soil health, preserve biodiversity, and restore ecosystem services, creating additional aesthetic values with higher social acceptance as compared with traditional strategies. Extending the longevity of remediation also minimizes the risks associated with contaminant rebound and migration, thus reducing the environmental and economic impacts in the long-term.

4. Integrate remediation and redevelopment

Remediation represents one crucial step in BRR; however, it should co-occur with redevelopment to maximize sustainability gains. Traditionally remediation and redevelopment are often conducted in separate phases, creating barriers for each other's optimization. Decisions are made based on narrow values and only reflect a portion of stakeholders at each phase. This conventional mode for BRR has caused a huge missed opportunity for synergies between remediation and redevelopment. To align sustainable remediation with sustainable redevelopment, it is imperative to incorporate various normative sustainable development principles, as well as to integrate diverse needs of different user groups [14,41]. Existing studies have shed light on two promising strategies implemented at brownfield sites: nature based solutions (NBS) and renewable energy generation, both of which are now discussed (Table 1).

Table 1. Environmental, social, and economic benefits of sustainable strategies integrating remediation with redevelopment

Sustainable strategies	Environmental benefits	Economic benefits	Social benefits	Disadvantages
Nature based solutions				
Construction of large urban park	Improved soil health; soil erosion control; carbon sequestration; reduce heat island effect; enhance flood control; improved ecosystem [152,153]	Low cost; increase property value in neighborhood [72,154]	Improve local livability; enhance hobbies and leisure activities; promote social cohesion; aesthetic value; improve spiritual health [152,154]	Occupation of large precious urban land; require long-term monitoring and financial arrangement [72,120]
Green and blue infrastructures incorporated into site landscape	Carbon storage by woody biomass; regulating microclimate; noise attenuation; healthy ecosystem [120,152]	Encourage inner city investment; enhanced flood control [154,155]	Aesthetic value; increase human-environment connection; improve spiritual health; stigma reduction [152,154]	Financial and administrative challenge in long-term operation and maintenance; slow contaminant removal rate [120,156]
Conversion to industrial heritage park	Reduce environmental footprint embedded in construction; mitigate heat island effect; provide local habitat for wildlife [120,157]	Utilize existing infrastructure; stimulate spending; increase tax revenue [154]	Heritage protection; enhance cultural diversity; encourage hobbies and leisure activities; promote educational activities; improve spiritual health [154,158]	Controversy about aesthetic value; potential health and safety hazard [159]
Sustainable energy generation				
Energy biomass	Reduce fossil fuel consumption and CO_2 emission; restore degraded land; reduce erosion [108,109]	Render economic competitiveness for phytoremediation [80]	Reduce competition with food production; enhance fuel price stability [160]	Not suitable for heavy contamination; potential contamination transfer to biofuel; air pollution; substantial water usage [161,162]

Solar power	Conserve greenfield; improve air quality; [59]	Reduce development cost; electricity cost saving; avoid zoning constraints; increase tax revenue; close to user and reduce transmission requirement [59,79]	Create jobs; shorten development timeframe [59,163]	Require sunny climatic condition; need appropriate site topography [164,165]
Wind power	Conserve greenfield; improve air quality [59]	Reduce development cost; avoid zoning constraints; increase tax revenue; close to user and reduce transmission requirement [59,79]	Employment benefit; aesthetic value; improve spiritual health [163,166]	Require windy climatic condition [164]
Heat pump	Reduce fossil fuel or electricity consumption; lower carbon footprint [167]	Low operation cost; short payback time [81,168]	Fuel poverty reduction; reduce energy bill for end users [169]	Technological robustness still need proof; high capital cost [168,170]

4.1 Nature based solutions

Brownfield sites are refuges for microorganisms, soil fauna, plants, and birds [171,172]. Traditional brownfield remediation and redevelopment often lead to losses of biodiversity [172,173]. Nature based solutions refer to BRR strategies that are inspired and supported by nature, simultaneously providing human well-being and biodiversity benefits [174]. They offer superior effect in BRR for improved ecosystem services include carbon sequestration, soil erosion prevention, nutrient regulation, biodiversity, aesthetic values, and air quality regulation [175,176]. Three most commonly used NBS for BRR are discussed here: conversion to urban parks, green and blue infrastructure, and conversion to industrial heritage parks, as they provide a diverse range of environmental, social, and economic benefits (Fig. 2d, Table 1).

Construction of large urban greenspace on potentially contaminated land represents a soft-use of brownfield that avoids sealing soil and maintains or enhances its biological function, serving as a wildlife habitat and bringing amenity and recreational value [59,120]. In Merseyside, UK, a 28-ha landfill site was converted to an urban park, which provides visitors with a scenic waterfront and a variety of walks. A qualitative multi-criteria analysis showed that this NBS had reduced environmental, economic, and social impact scores by 33%, 33%, and 50%, respectively [72]. In Beijing, China, a 173-ha petrochemical site was converted into a major urban park. Environmental monitoring data showed that the risk from soil and groundwater contamination at the park is low due to natural attenuation and that local biodiversity is greatly improved [153]. It is notable that it is not always possible to install a vegetation cover directly on a degraded brownfield. In this case soil construction serves as a promising assisting strategy for the ecological restoration, where fertile surficial soil layers are established with green waste compost, papermill sludge, crushed brick, rubble and other urban or industrial wastes [177,178]. Low environmental impact of this pedological engineering strategy lies in high carbon storage capacity of the artificial soil layer, as well as its potential as an alternative solution to waste landfilling [179,180].

Green and blue infrastructure (GBI), such as green landscaping and constructed wetlands, can be an attractive NBS for addressing low concentrations of pollutants in soil, groundwater and storm runoff at brownfields. In California, USA, eucalyptus and willow trees were incorporated into a brownfield landscape for the effective removal of organic pollutants via phytovolatilization [156]. In Brisbane, Australia, a constructed wetland was used at a brownfield site to treat contaminated surface runoff, which was reused for irrigation [181]. In Oslo, Norway, buried storm water pipes on brownfield land were converted into open watercourses, which reduced potential leaching of toxic substances from landfill sites, and provided new recreational space for urban residents [155]. These NBS systems are incorporated into urban landscape, rendering a variety of benefits, including aesthetic improvement, noise and dust reduction, and CO_2 sequestration [152]. Moreover, native plants can be used in GBI to further reduce the life cycle environmental impact in comparison with conventional brownfield landscapes [182].

Conversion of brownfield sites into industrial heritage parks represents another promising strategy. It can provide a recreational destination, while fulfilling the purpose of heritage protection and enhancing cultural diversity [158]. In Duisburg, Germany, a 20-ha brownfield site was developed into a heritage park which highlights industrialization history [120]. In Beijing, China, a 70-ha Shougang Industrial Heritage Park was built within one of China's largest steelworks, which became a major venue for the 2022 Winter Olympic games to enhance the sustainability of this mega-event [159].

Despite the multi-faceted benefits of NBS, there are also obstacles for their adoption. Plants can emit biological VOCs and toxic pollens, posing a potential public health risk [152]. This obstacle requires careful selection of plant species to mitigate. Nature based solutions also require continuous investment in long-term risk management and monitoring, which can sway private investment from choosing such strategies [120]. Financial arrangements may be established among the liability owner, land owner, and management entity to address such issues [183].

4.2 Renewable energy generation

Sustainable energy generation can serve as a catalyst for the integration of remediation and redevelopment at brownfield sites. The ongoing shift toward carbon neutrality and net zero places a strong demand for renewable energy, including biofuels, solar, wind, and geothermal energy (Fig. 2d) [184]. However, it is often hindered by local zoning requirements due to land constraints [79].

Derelict brownfield sites should be prioritized as suitable locations for rapid deployment of such sustainable energy projects by local governments [164]. Wind and solar energy on brownfields is attractive for developers because it can reduce the development project cycle due to streamlined permitting and zoning and improved project economics [163]. In New York, USA, 14 wind turbines were built on a 12-ha former steel mill site to generate electricity (34 MW), bringing green energy and economic revival to the local community [166]. In Massachusetts, USA, solar panels (3 MW) were installed on a 5-ha former landfill site, as part of helping the city to reach its 100% renewable energy goal [165]. In Michigan, USA, it was estimated that the total wind and solar energy potential at its brownfield sites was over 5,800 MW, which is equivalent to 43% of the entire state's residential electricity consumption [79].

The growing of plants for energy biomass on marginal land, such as brownfield sites, holds great promise [185]. A variety of plant species may be used to remove or stabilize soil pollutants while also supplying a useful end product such as bioethanol, biodiesel, and charcoal or biochar [186], which can render substantial life cycle environmental benefits for phytoremediation [108]. In Spain, a phytoremediation system coupled with bioenergy harvesting was found to reduce global warming potential, acidification potential, and eco-toxicity potential by 80%, 83%, and 91%, respectively, in comparison with a biomass disposal option [109]. To further strengthen the feasibility and sustainability of such systems, more effort is required to enhance water use efficiency, biodiversity conservation, avoiding pollution transfer, and stakeholder engagement [161,162].

Aquifer thermal energy storage (ATES) can be integrated into the bioremediation of contaminated soil and groundwater to render sustainability synergies [167]. The temperature of shallow groundwater is relatively constant year-round; therefore, it can be extracted and re-circulated for space heating in winter and cooling in summer. The improved flow condition and rising groundwater temperature in ATES can be used to enhance in-situ biodegradation [170]. When compared with conventional separate operations, this sustainable integrated system can reduce life cycle greenhouse gas emission by 66% (ref [167]). This technology has been proved with a field demonstration; however, further technological advancement is required to address several challenges for wider commercial application. In particular, detachment of microbial biomass, fluctuation in subsurface redox condition, and chemical and biological clogging need to be mitigated [170].

5. Resilience in a rapidly changing world

Sustainability of BRR is not only affected by aforementioned issues, but also challenged by global changes in the Earth system. Alterations in geophysical conditions, such as flooding and sea level rise, pose a challenge to the resilience of remediation systems. Millions of people live in the vicinity of contaminated sites who are increasingly vulnerable to flooding and sea-level rise driven by climate change [183]. Inundation and infiltration at contaminated sites could facilitate the spread of pollutants due to surface runoff and contaminated groundwater migration [187]. In this context, ecosystem service of remediated land must be improved to build resilience against these changes. In the face of these changing conditions, passive treatment technologies like PRB and tree-based hydraulic control systems require proof of resilience [156,187]. 100-year modeling under various climate change scenarios suggested that phytoremediation at a coastal brownfield site had good resilience to rising temperature, climatic water deficit, and moderate sea-level rise; but under extreme sea-level rise scenario, the complex system would pass a tipping point that drastically increased the environmental risk [156].

Site remediation also needs to consider changing social conditions. For instance, during historical urbanization, many urban rivers were converted to underground watercourses; for example, Denmark and Sweden have 15% and 20% river lengths lost to pipes, respectively [188]. For underground pipes located in brownfield land, increased precipitation levels due to climate change is a high risk. Leaks and overflow from aged pipes can result in increased leaching of soil pollutants, threatening both groundwater and adjacent surface water [155]. On the other hand, scientific discovery and the continuous improvement of living standards can lead to more robust public health standards and reduced acceptable risk level. For example, in the USA until 2012, the childhood blood lead level of concern was >10 μg/dL. The CDC now uses a more stringent blood lead reference value of 3.5 μg/dL. Such changes in acceptable risk level could in turn result in repeated risk-based remediation and impose substantial costs [15]. Another grand challenge is emerging contaminants that come to spotlight based on new scientific findings. Contaminants like PFAS was not a target of remediation 10 years ago, but it is becoming a brownfield site constituent of concern (COC) nowadays in many countries; microplastic and nanoplastics are not a brownfield COC for now, but based on an increasing body of evidence showing their prevalence, toxicity, and exposure pathways, they may become future brownfield COC.

Hence sustainable remediation must be inherently resilient to these changing geophysical (such as climate change and pollution migration) and social conditions (such as more stringent regulatory standards and new development needs) (Fig. 4). Remedial systems need to be resistant to future changes; and as changes become so significant that intervention is inevitable, existing remedial systems must be designed with high levels of adaptability to avoid double effort [15]. Resilient remediation strategies might require higher initial investment, but can result in better life cycle return of environmental and social benefits (Fig. 4). Landscape design can also greatly improve BRR resilience by taking into account the evolving scientific understanding of exposure risks and changing public policies [189]. Physical barriers such as capping systems can help to mitigate risks from flooding and erosion, rendering higher resilience to changes in geophysical conditions (Fig. 4). For instance, a contaminated soil capping system at a site in Washington, USA, was doubled in size to provide greater resilience to more frequent severe storms [183]. Converting underground storm pipes into surface water courses, as part of a NBS on brownfield land, is one way to adapt to extreme climate events, because above ground river system render additional flood pathways and infiltration capability [155]. Woody plants used in phytoremediation can also help mitigate flooding risk in certain locations [152]. For brownfield sites with residual contaminants and post-remediation management, it is necessary to conduct more frequent groundwater monitoring during precipitation and drought periods because contaminant concentrations are directly affected by these processes [187].

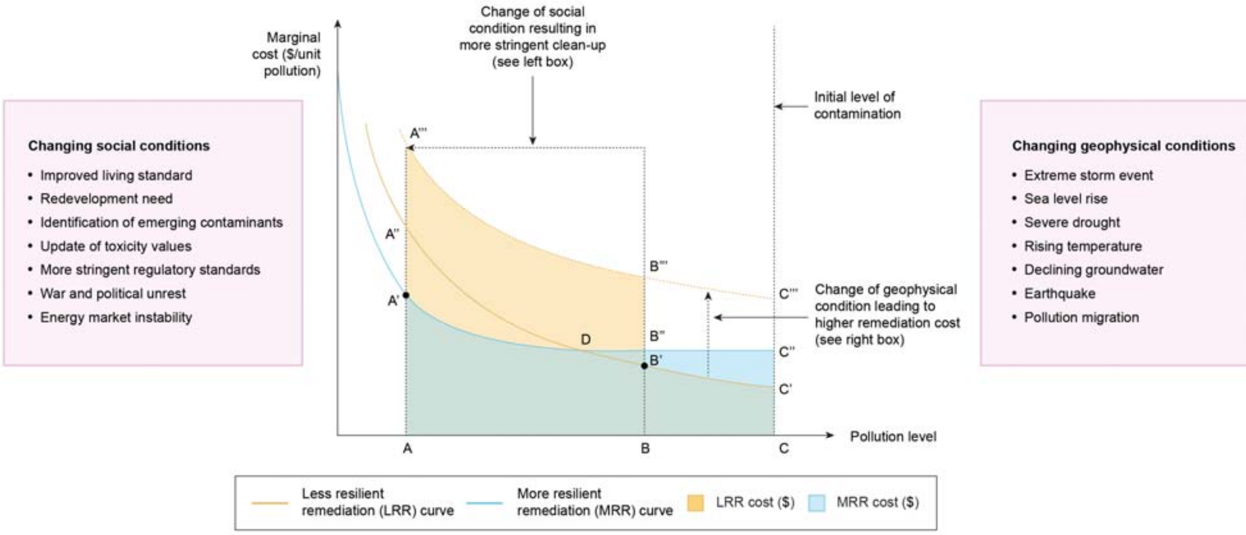


Fig. 4. Resilience of sustainable remediation approaches under changing social (left box) and geophysical conditions (right box). Resilience is achieved via two aspects: (1) more resistant to change in geophysical conditions, such as climate change and pollution migration; and (2) imposing lower marginal cost if more stringent cleanup is needed due to social change, such as improved living standard and redevelopment need. A more resilient remediation (MRR) strategy might initially render higher cost (the area surrounded by BCC''B'') than a less resilient remediation (LRR) strategy (BCC'B'); however, MRR cost over the long term (ACC''A') can be much lower than LRR cost (ACC'B'B'''A'''). A resilient remediation strategy is more resistant to changes in geophysical conditions and social conditions. Figure modified, with permission, from [15].

6. Summary and future perspectives

Sustainable remediation offers multi-faceted opportunities to alleviate challenges posed by land contamination. It aims to internalize the indirect environmental costs, and to maximize wider social and economic benefits. Sustainable immobilization, low-impact bioremediation, novel in-situ chemical treatment, and innovative passive barriers are promising remediation strategies; moreover, the integration of sustainable remediation with redevelopment can further maximize environmental, social and economic benefits. However, several challenges still remain for sustainable BRR, where future research efforts are much needed.

The first challenge is how to reconcile different value considerations by various stakeholders. Many environmental, social, and economic impacts are external to the traditional financial model that governs BRR decision-making processes. The direct and indirect impacts associated with BRR has meant the economic value of brownfield is often discounted. Therefore, broader recognition of the socioeconomic and environmental benefits in the context of sustainable development is much needed. It requires a concerted action of developers and other stakeholders [14]. Future research studies must capture both tangible and intangible value considerations, ideally covering both attributional and consequential impacts. Local stakeholder engagement is essential in balancing the trade-offs and different priorities. Therefore, it is important to conduct comprehensive assessment in a quantitative manner to render more convincing results. Sustainability can only become relevant in decision making when the indirect costs are quantifiably measurable and fully transparent. Moreover, social impact assessment is often lacking or conducted using subjective methods [41], which can be difficult for various stakeholders with distinctive disciplinary backgrounds to reach consensus. Future studies need to develop objective and quantitative assessment methods that can aggregate a wide range of value considerations, thus making the results visible to policy makers and practical decision makers.

The second challenge is how to better align sustainable remediation with the net zero transition. Carbon neutrality, which has become a new mandate for the entire economy, will undoubtedly influence the adoption of sustainable remediation. In comparison with traditional remediation methods, sustainable remediation technologies can typically reduce the life cycle greenhouse gas emission by 50%~80% (refs [45,103,109]), and some innovative functional materials can reduce carbon footprint by over 95% (ref [149]). Biochar derived from biological waste can even be used in soil remediation to achieve negative carbon footprint. However, green remediation methods are often less efficient, requiring long periods to achieve target cleanup goals or requiring long-term post-remediation risk management. Moreover, innovative functional materials can be cost prohibitive, unless they can be synthesized on a massive scale with significantly lower cost. Both issues need to be alleviated by technology advancement and technology diffusion. On a city-level, brownfield remediation and redevelopment also offers substantial climate change mitigation because it reduces household energy consumption, commute distance, and infrastructure construction need. However, research-informed policy instruments are much needed to incentivize decision makers.

Thirdly, the integration of remediation and redevelopment requires more policy innovation and inter-disciplinary collaboration to enable wide application. Traditionally remediation and redevelopment phases have often been separated sequentially. Their integration into parallel phases can bring substantial sustainability benefits; however, existing literature on BRR often lacks a multi-disciplinary lens that can fully capture all pertaining value considerations. Moreover, the determinants of environmental, social and economic benefits are not well understood. Ethics and equality are almost never considered in the assessment tools. Remediation and revalorization of brownfields make the city sites and neighborhoods more attractive and increases land price, rents and the overall cost-of-living, thereby forcing lower-income communities to be displaced elsewhere [192]. New governance mode ought to be more inclusive and help to overcome this challenge, although the political and power aspect that is inherent within inequality issues needs to be simultaneously addressed [193]. Nature based solutions and sustainable energy systems hold huge potential, but they are encountering obstacles in deployment and market penetration. There is a strong need for research collaboration between environmental engineers and urban planners to identify smart strategies, as well as enhanced information transfer and collaboration between environmental and planning regulatory agencies to materialize the full potential [194]. When facing future uncertainties and global environmental changes, remediation systems must also be inherently resilient. By addressing these dynamic issues, sustainable brownfield remediation and redevelopment can offer a revolutionary opportunity for urban revitalization and socio-ecological transformation.

Glossary

BACK DIFFUSION
The contamination of a high permeability zone of groundwater aquifer by the diffusive transport of contaminants out of an adjacent low permeability zone.

BIOCHAR
A solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment.

BIOSTIMULATION
The addition of rate-limiting nutrients to groundwater to stimulate contaminant degradation by native microorganisms.

BIOAUGMENTATION
The addition of microorganisms to groundwater for contaminant degradation.

BROWNFIELD
Former developed sites that are derelict or underused due to potential or perceived contamination of soil and groundwater by hazardous substances.

DIG & HAUL

The excavation and off-site disposal process of contaminated soil, which require a pre-treatment procedure sometimes in order to meet land disposal restrictions.

GREENFIELD
An area of land that has not previously been developed.

HYDRAULIC CONTROL
A technique used to control the movement of contaminated groundwater.

IMPACT HOT SPOT
The category with much higher life cycle impact as compared with others.

LAYERED DOUBLE HYDROXIDES
A class of synthetic clay minerals with brucite-like cationic layers containing anions in the hydrated interlayer for charge balance.

NATURE BASED SOLUTION
Remediation strategies that are inspired and supported by nature, simultaneously providing human well-being and biodiversity benefits.

PERMEABLE REACTIVE BARRIER
A passive system for in-situ groundwater remediation, where contaminated water passes through the active material with high permeability, contaminants being sorbed or degraded.

PHYTOREMEDIATION
The use of plants to extract (phytoextraction), stabilize (phytostabilization), degrade (phytodegradation and rhizoremediation), or volatilize (phytovolatilization) contaminants either from the unsaturated soil vadose zone or groundwater.

PUMP & TREAT
An ex-situ remediation system where contaminated groundwater is pumped from the subsurface, treated above ground, and discharged.

SCENARIO ANALYSIS
Analysis of different possible situations relevant for life cycle assessment applications based on specific assumptions.

SENSITIVITY ANALYSIS
Analysis of the robustness of results and their sensitivity to uncertainty factors in life cycle assessment.

SOLIDIFICATION/STABILIZATION
A remediation technology where contaminated soil is physically bound and enclosed within a solidified matrix, or chemically reacted and immobilized by the stabilizing agent.

SUSTAINABLE REMEDIATION
Remediation strategies and technologies that maximize the net environmental, social, and economic benefits.

SYSTEM BOUNDARY
Boundaries for which processes in brownfield remediation that is included in the life cycle analysis.

THERMAL DESORPTION
A physical process designed to remove volatile contaminants from soil via heating.

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Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 42225703) and and National Key Research and Development Program of China (Grant No. 2020YFC1808000).

Competing interests

The authors declare no competing interests.

Author contributions

DH: conceptualization, data analysis, writing
AA: review/editing
DC: review/editing
QH: review/editing
YZ: review/editing
LW: data collection, review/editing
NK: review/editing
YSO: review/editing
DT: review/editing
NB: review/editing
JR: review/editing

Publisher's note

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Sustainable remediation and redevelopment of brownfield sites

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Abstract

Anthropogenic activities have caused widespread land contamination, resulting in the degradation and loss of productive land, deterioration of ecological systems, and detrimental human health effects. To provide land critical for future sustainable development, remediation and redevelopment of the estimated 5 million global brownfield sites is thus needed. In this Review, we outline sustainable remediation strategies available for the cleanup of contaminated soil and groundwater at brownfield sites. Conventional remediation strategies, such as dig & haul and pump & treat, ignore externalities including secondary environmental burden and socioeconomic impacts such that their life cycle detrimental impact can exceed their benefit. However, a range of sustainable remediation technologies offer opportunities for urban revitalization, including sustainable immobilization, low-impact bioremediation, novel in-situ chemical treatment, and innovative passive barriers. These approaches can substantially reduce life cycle environmental footprints, increase the longevity of functional materials, alleviate potential toxic by-products, and maximize overall net benefits. Moreover, the integration of remediation and redevelopment through deployment of nature-based solutions and sustainable energy systems could render substantial social and economic benefits. While sustainable remediation will shape brownfield development for years to come, ethics and equality are almost never considered in assessment tools, and long-term resilience needs to be addressed.

1. Introduction

4.2 billion (55%) of the world's population currently live in urban areas, with that number expected to increase by 2.5 billion people before 2050 (ref [1]). This growth is happening at a time when the nature of urban economic activity is shifting; industrial sites that were once at the heart of industrialized urban centers are increasingly passing their economically productive lifespan and abandoned [2]. A vast number of these previously-developed sites stay derelict or underused due to urban planning controls or land use restrictions relating to the potential of soil and groundwater contamination by hazardous substances [3]. This so-called "brownfield" land (contrasting with undeveloped "greenfield" land) [2] is numerous. Using data from 35 countries and regions, we established a polynomial relationship between the number of sites per 1,000 population and per-capita GDP. Combining literature data and calculated results, we estimate that globally there are >5 million potentially contaminated sites (namely, brownfield sites) (Fig. 1).

These brownfield sites are associated with a variety of nuisances. Toxic heavy metals and volatile organic compounds (VOCs) are released from piled solid wastes, leaked pipelines, broken storage tanks, and wastewater ponds, causing the contamination of adjacent soil, water, and air, leading to visual and odor nuisances [6]. The contaminants further migrate in anisotropic, heterogeneous aquifers underneath the site, which further pose a hidden threat to human health due to groundwater pollution (as a drinking water source for urban dwellers) and vapor intrusion [7,8]. The brownfield sites are also associated with a variety of social and economic issues. Due to perceived risk associated with brownfield sites (Fig. 2a and 2b), nearby property value would be depreciated in comparison with market value and attract the poor [9]. Minority groups are more likely to live near contaminated sites, implying indirect discrimination and environmental injustice [10,11].

Land recycling of these numerous brownfield sites offer opportunities for land management [12]. The rapid increasing speed of global land take for settlement, which would double in 2050 as has been estimated by the United Nations [12], highlights the necessity for the reuse and revitalization of these derelict lands. Indeed, the adoption of the "no net land take by 2050" initiative by the European Commission implies that nearly all future urbanization in the EU will need to occur on brownfield sites [13]. While the benefits of brownfield remediation and redevelopment (BRR) are clear—including reduced human health risks, racial and health injustices, and crime and incivilities, as well as economic growth [9]—traditional BRR (Box 1) is often hindered by high cost, cumbersome administrative processes or uncertain remediation performance [14].

However, the emerging concept of sustainable remediation holds promise to accelerate BRR by minimizing adverse side effects and maximizing net benefits [15]. Sustainable remediation is drawing attention on account of three important factors: the recognition of the life cycle adverse impact of traditional remediation, institutional pressures exerted by new industrial norms, and stakeholder demand for sustainable practice [15], the latter driven by, and resonating with, the UN World Commission on Environment and Development [16] and the Sustainable Development Goals (SDGs) of the UN 2030 Agenda [17].

Yet, there are also concerns that businesses will use this concept for "green washing", claiming a remediation project or technology is sustainable without robust evidence [18], or to simply reduce project costs for liability owners by doing less remediation [19]. Thus, it is vital to better understand the holistic impacts of remediation and redevelopment so as to materialize the full potential of sustainable remediation practices.

In this Review, we outline sustainable strategies for brownfield remediation and redevelopment. We begin with a discussion of the primary, secondary and tertiary impacts of traditional practices over the life cycle of remediation. Then, we summarize promising sustainable strategies, namely, innovative in-situ soil and groundwater remediation technologies and strategies that integrate remediation with redevelopment. We end with identification of challenges and future research directions.

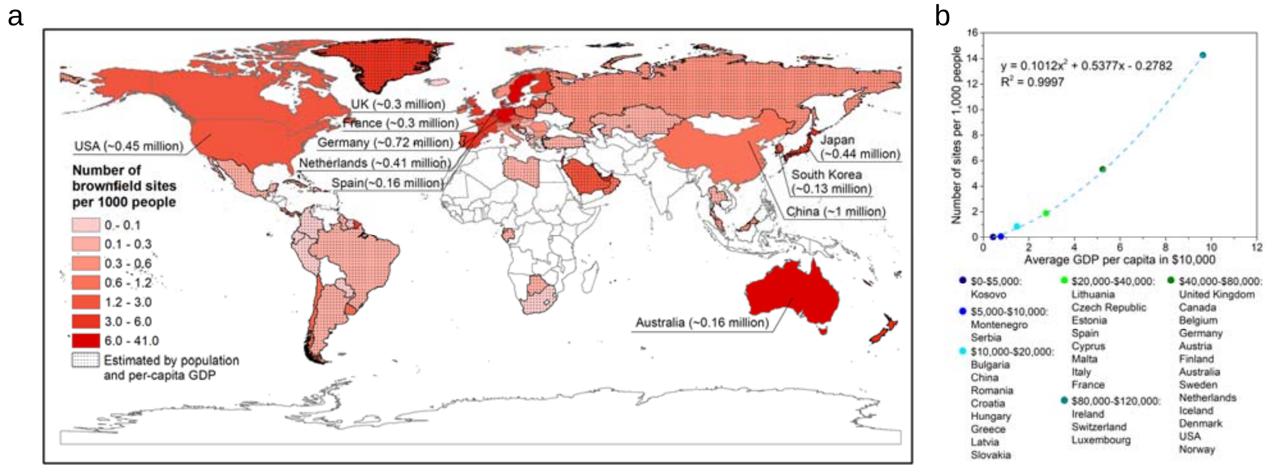


Fig. 1. Global number of brownfield sites: a| Country-level number of brownfield sites, with the top 10 countries labeled. The number of brownfield sites per 1,000 people is color coded, countries with literature data solid, and estimates for other countries derived using population and per-capita GDP data hatched. b| a polynomial relationship between sites per 1,000 population and per-capita GDP based on grouped average values [3-5,20,21]. The number of contaminated sites is estimated to exceed 5 million.

Box 1. Traditional brownfield remediation and redevelopment (BRR) strategies.

Dig & Haul, also known as excavation and off-site disposal, is the most widely used BRR strategy due to its simplicity of operation. It involves the excavation of contaminated soil, transport, and off-site disposal. Pre-treatment is necessary sometimes to meet disposal requirements [24,25]. Dig & haul involves the transportation of a large quantity of contaminated soil through populated areas. It also faces the problem of long-term landfill operation, potential leakage and associated liability.

Pump & Treat is a groundwater remediation strategy, which includes retrieval of contaminated groundwater using extraction wells, or trenches, cleanup in above ground treatment system (either on-site or off-site), and final discharge of treated water. This technology was traditionally designed for contaminant mass removal, but often with long operation periods, sometimes up to several decades, due to diminishing efficiency associated with back diffusion from aquifer matrix. Nowadays it is more often designed to manage plume migration [26,27].

Thermal desorption refers to the process where soil contaminated by volatile contaminants is heated at a temperature typically ranging from 90 to 560 °C, so that these contaminants can be physically separated from the soil matrix, and treated with an off-gas treatment system [30,31]. This thermal treatment technology is highly energy intensive, rendering a high carbon footprint.

Chemical treatment makes use of oxidation and reduction agents for the remediation of organic contaminants or hexavalent chromium in contaminated soil or groundwater. It can be conducted either ex-situ (mixing soil with agents following excavation) or in-situ (injection of agents to vadose zone or groundwater). Typical oxidation agents include ozone, peroxide, permanganate, persulfate, while reduction agents include zero-valent iron (ZVI), ferrous iron, polysulfides, and sodium dithionite [22,23]. The manufacturing of these reagents often renders high environmental footprint, and in some case their application also results in toxic byproducts.

Solidification/Stabilization (S/S) is a soil remediation strategy, where contaminated soil is mixed with binding agents either in-situ or ex-situ [28,29]. The contaminated soil is physically bound and enclosed within a solidified matrix (solidification), or chemically reacted and immobilized by the stabilizing agent (stabilization). Labile forms of contaminants are immobilized into less-labile forms during this process, thus rendering lower leachability. Cement is the most widely used S/S agents, but it also renders high environmental footprint.

2. Life cycle impact of brownfield remediation and redevelopment

Traditionally, brownfield remediation was considered as "inherently sustainable" because it involves removing toxic chemicals from the environment, frees up contaminated land for reuse, and reduces urban sprawl. However, many environmental and socioeconomic externalities associated with remediation activities have been uncovered based on holistic sustainability assessment (Fig. 2). In sustainable remediation terminology, the type of impact can be divided into primary, secondary, and tertiary impacts (Box 2) based on their relationship to site boundary and site use. Life cycle based approaches have often been used to compare various technologies and identify the most sustainable strategy, as well to recognize impact hot spots and identify opportunities for optimization by sensitivity and scenario analyses. This section discusses various aspects of life cycle impact of traditional BRR practices. Note that assessment frameworks, such as life cycle primary-tertiary impacts (Box 2), also apply for sustainable BRR strategies to be discussed in Section 3.

2.1 Environmental impact

Development on brownfield land with contaminated soil and groundwater can have serious environmental consequences. For example, a former chemical dumpsite in New York, USA was developed for residential housing and schooling. Exposure to toxic substances in the soil and groundwater increased chromosomal damage among local residents by over 30 times [32]. Therefore, remediation is often required pre-redevelopment in order to mitigate the environmental risk, rendering substantial health benefits for local neighborhoods. Aggregated analysis of a large number of sites has shown that remediation can reduce the chance of children living within 2-km lead contaminated sites having elevated blood lead levels (BLL) by 13~26% (ref [33]), leading to a 20~25% reduction in infant congenital anomalies within 2-km of remediated superfund sites [34]. On the other hand, cleanup activities are associated with significant detrimental environmental impacts themselves. A sustainability assessment of the remediation of a single brownfield site in New Jersey, USA, calculated the potential to emit 2.7 million tons of CO_2 if a dig & haul - the most widely used traditional remediation approach [35] - was implemented at the site. This figure is equivalent to 2% of the annual CO_2 emissions for the entire state [15,36].

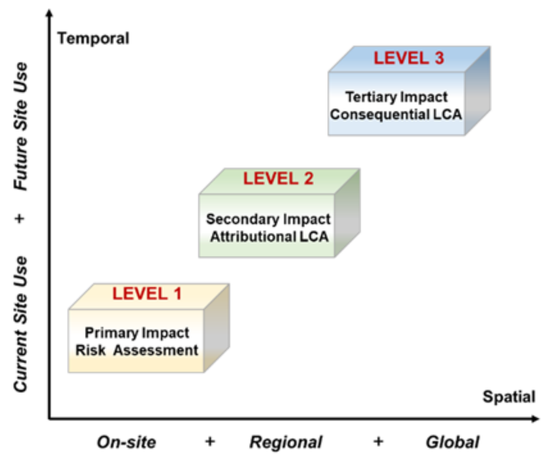
The environmental impact of brownfield remediation can extend well beyond the spatial boundary of the site or even local communities [37]. The impacts are associated with upstream processes like off-site fossil fuel burning as an energy source and the acquisition of remediation materials, and downstream processes like off-site hazardous waste disposal and long-term maintenance, in addition to the on-site remediation activities like soil excavation, groundwater extraction, and in-situ chemical oxidation [38]. Environmental impact assessments have tended to include three major categories: ecology, human health, and resource, but the specific impact indicators are more diverse, with global warming, human toxicity, and eco-toxicity potentials often being the most notable indicators [38]. Studies have shown that the sum of the detrimental environmental impact of remediation can exceed that of no-action being taken, posing doubt on the legitimacy of conducting aggressive remedial actions (Box 2). Due to the recognition of detrimental environmental impacts during remediation, the USEPA is actively promoting green remediation as a way to minimize the life cycle environmental footprint [39], while European practitioners seek sustainability assessment to maximize the net benefit of remediation [40].

The state of brownfield being derelict and the duration of remediation also renders implications to life cycle environmental impact. Slow pace in brownfield remediation and redevelopment means that new urban development would occur on greenfield. Greenfield sealing jeopardizes its socio-ecological functions in supplying groundwater, producing oxygen, regulating micro-climates, and providing recreational value [14]. In this perspective, more rapid remediation technologies, like dig & haul and thermal desorption, provide a positive environmental value. Life cycle impact assessment (LCIA) that incorporates land resource as a midpoint indicator may be used to capture this intangible benefit [41]. Alternatively, the environmental impact can be captured by expanding the system boundary to include the substitution of brownfield redevelopment with greenfield development. A city-level assessment using this approach found that brownfield redevelopment compared to greenfield development in the San Francisco Bay Area of California, USA, could reduce greenhouse gas emission by 14% over a 70-year period [42]. This is because it would significantly reduce commute distances, cut back energy demand for space cooling and heating, as well as requiring less new road and utility infrastructure [43]. In order to fully capture the extended environmental impacts, it is also essential to consider a wide range of social impacts associated with brownfields.

Box 2. Primary, secondary, and tertiary impacts of brownfield remediation

Traditional decision-making for brownfield site remedy mainly focuses on the site itself. However, evidence has shown that impacts of a remedy go beyond the site spatial and temporal boundaries, affecting a larger scale and a longer time series. Hence a holistic view that goes beyond site boundary and looks beyond the contemporary time horizon should be required. In sustainable remediation typology,

- Primary impact refers to those caused by the toxic substances initially present in environmental media at a brownfield site, including contaminated soil, groundwater, and sediment [44].
  - Typical primary impact includes carcinogenic and non-carcinogenic human toxicity from oral, dermal, or inhalation exposure, eco-toxicity due to plant uptake or bioaccumulation in food webs.
  - Primary impact is quantified using long-term monitoring data or predictions based on contaminant fate and transport modeling [45]. The quantification of primary impact is critical in comparing remedial alternatives [46]; however, most existing remediation LCA studies lack its inclusion, which can result in misleading conclusions [47].



- Secondary impact refers to those associated with the remediation activities [45].
  - They can include all pertaining cradle-to-grave processes, such as the environmental footprint of electricity generation, equipment manufacturing, and remediation reagent synthesis [48]. Researchers have used various system boundaries to exclude some minor processes or common processes that do not directly relate to a decision regarding remediation choices [37]. Secondary impact is included in most remediation sustainability assessments, often using the LCA method.
  - The comparison of primary impact and secondary impact can decide whether remediation renders net environmental benefit [47]. For example, the remediation of a trichloroethene contaminated site in Denmark using thermal desorption or dig & haul methods could increase the carcinogenic human toxicity by 2 times and 7.6 times, respectively, implying both strategies were less desirable than taking no action from the human toxicity perspective [45].
- Tertiary impact refers to those associated with post-remediation brownfield site usage [49].
  - While both primary and secondary impacts are attributional, namely, reflecting the average environmental burden associated with completing a functional unit of remediation service [45], tertiary impact is consequential, that is, reflecting how various brownfield remediation options affect environmental relevant flows to and from the site during the post-remediation phase [50].
  - Tertiary impact has drawn much less attention than primary and secondary impacts in sustainability assessment studies. It was first conceptualized in a LCA of BRR in Montreal urban core, Canada [49]. Follow-up LCAs have shown that tertiary impact can well exceed primary and secondary impacts in magnitude [37], which suggests that the integration of remediation and redevelopment could greatly benefit sustainable remediation, because tertiary impact is mainly dependent on redevelopment strategies.

2.2 Social impact

Brownfield sites are often disconnected from the local urban context and represent a social stigma [51]. Brownfield remediation and redevelopment can bring a range of social benefits, including the revitalization of deprived urban community, supplying new jobs, providing new housing, improved public health, and reducing urban sprawl [52]. But remediation activities can render negative social impact in themselves. For example, remediation workers might lack sufficient awareness and protection against potential hazards at brownfields [53]. Remediation operation can also cause serious secondary pollution and affect the local community. In Changzhou, China, remediation operation at a former chemical plant site caused pungent smell at an adjacent middle school, and hundreds of students attributed their abnormal health condition to secondary pollution from the remediation project [54].

Social impact is generally underrepresented in sustainable remediation literature [36,52]. Newly developed sustainability assessment frameworks and tools are starting to include more social impact indicators [55]; however, they are still very limited in comparison with environmental impact. A literature review of thirteen sustainability assessment tools found that human health and safety was the only social criterion included in all tools [56]. In contrast, ethics and equality are almost never considered in the assessment tools, even though this impact category is considered highly relevant to brownfield remediation [40,57]. Moreover, the assessment of social impact is usually subjective in existing appraisal tools [41], making it difficult to systematically use in decision making.

Brownfield remediation and redevelopment requires concerted intervention from various stakeholders in order to properly take the various social impacts into account [14]. Greenfield development is more attractive to land developers because there are less uncertainties and project schedule is more controllable [58]. Due to the direct and indirect social impact associated with brownfield, the economic value of land is often discounted, which can persist even after remediation is conducted [59]. Therefore, the revival of brownfield sites requires a broad recognition of the social benefits and to put them in the context of economic development.

2.3 Economic impact

The economic impact of brownfield remediation consists of both direct and indirect economic impacts. The direct impact mainly entails the financial cost of carrying out remediation projects including both short-term capital cost and long-term maintenance cost [60], as well as the financial return from selling or redeveloping a brownfield site and pertaining "opportunity cost" [61] (Fig. 2). The investment return depends on the choices of remediation and redevelopment strategies (Fig. 2c and 2d). This has been a cornerstone of traditional decision making in prioritizing remediation among a large portfolio of brownfields [62]. At brownfield sites that are financially non-profitable, public funding or other incentives are required to promote BRR [63], for which the indirect economic impact derived from environmental and social benefits must be accounted for.

Brownfield remediation and redevelopment can reduce health care cost associated with contamination exposure, attract public and private investment, improve employment and local tax revenue, lower crime rates and associated law enforcement costs [64]. Contingent valuation analysis at a brownfield site in Athens, Greece, showed that local residents were willing to pay 0.23% to 0.44% of their income for environmental cleanup alternatives [65]. The economic impact of BRR is also reflected in the local housing market. A hedonic pricing model showed that brownfield cleanup in the US can increase the value of properties within a 5-km radius by 5% to 11.5% (ref [9]). The cleanup of hazardous waste sites was found to increase nearby property values by 18.7~24.4% (ref [66]). Due to the increase of property value, local tax revenue near 48 remediated brownfield sites was estimated to increase by $29 to $73 million per year, which was 2~6 times that of USEPA's spending on the cleanup of those sites [67]. BRR allows new businesses to emerge and draw new employment on redeveloped sites, for instance, 246,000 new jobs created on 650 remediated Superfund sites in the US [68]. Besides these tangible benefits, cost-benefit analysis (CBA) can account for a wider range of environmental and social impacts using monetary terms over a longer time horizon [69].

The direct and in-direct economic impacts of remediation often spilt in opposite directions: the former as a cost on the liability owner or land developer and the latter as a benefit to the greater society. They can be reconciled by stakeholder engagement involving local government, site owners, land redevelopers, future site users, and the local community [70]. However, in reality, BRR is often hindered due to imperfect information, the financial burden associated with uncertain project duration, and liability concerns [71]. Moreover, decision making tools, like CBA, encompass a broad range of costs and benefits, which are not universally accepted by all stakeholders [59]. Existing published studies have often focused on specific case study sites, rendering difficulties in transferring these results to metropolitan or regional level decision making [71]. Some important value considerations may be non-quantifiable due to lack of data. For instance, the economic value of brownfield ecosystem services are largely an unknown [71]. Therefore, their usefulness in evaluating soft reuse strategies like nature based solutions (NBS) maybe limited or even controversial [72]. Future quantitative economic assessment tools will need to address these challenges by providing more transparent, standardized, and, importantly, justified monetization parameters and assumptions.

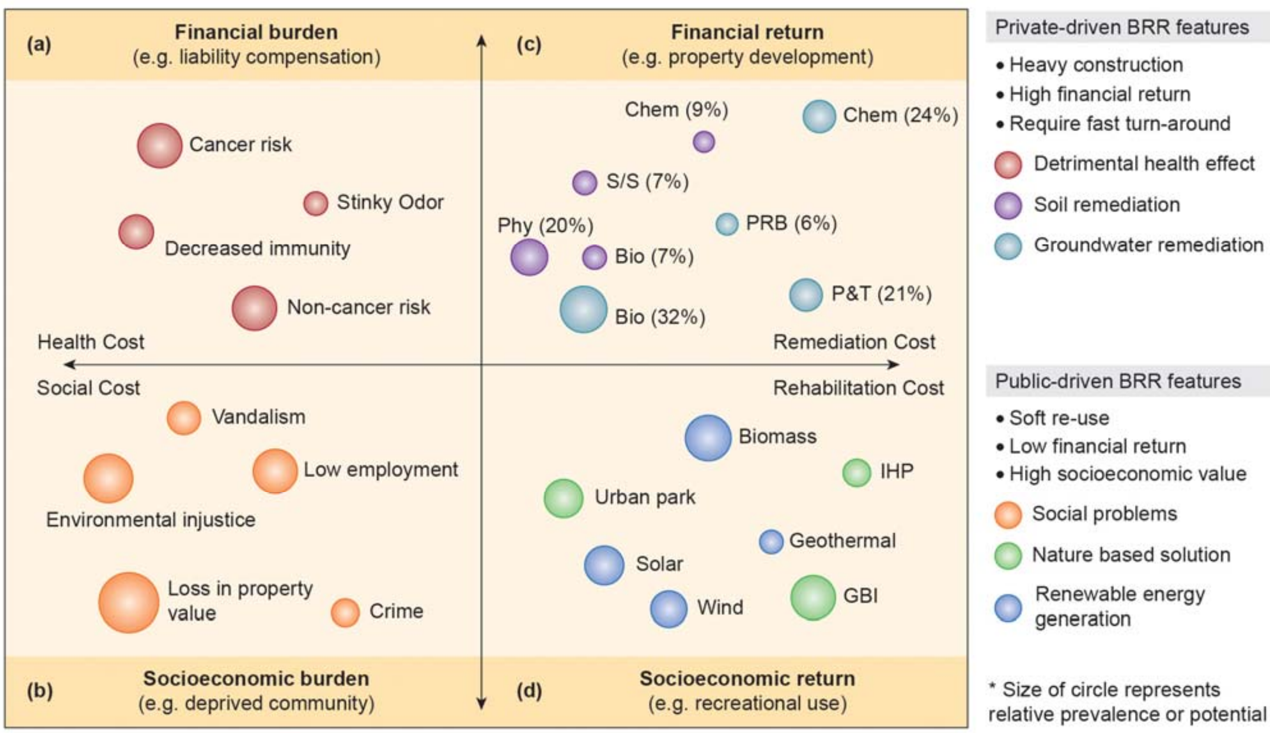


Fig. 2. Social and economic impact comparisons of brownfield remediation and redevelopment strategies. a| Health cost associated with contamination at brownfield sites [73-76]. The x axis represents the health cost, while the y axis represents the financial burden. Larger circle represents higher relative prevalence of a certain issue (qualitative). b| Social problems of derelict brownfield sites [10,51,77]. The x axis represents the social cost, while the y axis represents the socioeconomic burden. Larger circle represents higher relative prevalence of a certain issue (qualitative). c| Remediation cost versus financial return of various treatment technologies, percentage of market share based on US Superfund data in 2013~2017 (ref [35,78]). The x axis represents the remediation cost, while the y axis represents the financial return. Larger circle represents the percentage of market share (quantitative). d| Rehabilitation cost versus socioeconomic return of various BRR integration strategies [59,79-81]. The x axis represents the rehabilitation cost, while the y axis represents the socioeconomic return. Larger circle represents higher potential for the rehabilitation return (qualitative). Bio=bioremediation; BRR=brownfield remediation & redevelopment; Chem=chemical treatment; GBI=green and blue infrastructures; IHP=industrial heritage park; Phy=physical separation; P&T=pump & treat; PRB=permeable reactive barrier; S/S=solidification/stabilization. These social and economic burdens and returns are crucial factors that should be considered to judge whether a BRR is sustainable.

3. Sustainable remediation technologies

Considering the significant environmental, social, and economic impacts associated with traditional remediation strategies, technological innovation is required to maximize the sustainability potential of remediation. A number of novel, sustainable remediation technologies have emerged, including sustainable immobilization that uses novel binding agents with low carbon footprint to achieve contaminant passivation, low-impact bioremediation that uses plants and/or microorganisms to extract, stabilize, or degrade contaminants, novel in-situ chemical treatment that uses nanomaterials to achieve long-term effectiveness, innovative passive barrier system that incorporates novel filler materials with high selectivity, bio-electrokinetic remediation that uses microbial fuel cells (MFCs) for contaminant removal, low-impact soil washing that uses biodegradable chelating agents to enhance contaminant desorption from soil solid particles, and low-temperature thermal desorption that reduces energy consumption for contaminant volatilization. In this section, the first four sustainable remediation technologies that hold promise in maximizing the net benefit of brownfield remediation are discussed. These four technologies were selected primarily on the basis of technology maturity, and secondarily based on the results from previous life cycle assessments that compared the environmental, social, and economic impacts of different methods in specific cases. It should be noted that the net benefit and sustainability of any specific technology will be dependent upon site specific characteristics, and alternative technologies that are not discussed here may be more sustainable under certain site conditions.

3.1 Sustainable immobilization.

Sustainable immobilization represents an evolution from the traditional remediation approach of solidification/stabilization (S/S) of contaminated soil. The S/S method has been used for many years as an effective and relatively cheap way to immobilize heavy metal contaminants within the soil matrix (Box 1, Supplementary Fig. 1) [82]. However, the solidification part of S/S usually relies upon the introduction of Portland cement (PC) into contaminated soil, which renders a high carbon footprint (Supplementary Table 1), with cement manufacturing being the 3rd largest anthropogenic source of CO_2 emissions [83]. Hence the key to sustainable solidification is to lower the environmental impact by replacing Portland cement into greener and alternative cementitious binders. A wide varieties of novel binders have been developed, such as cement free clay-based binders, and alkali activated fly ash/slag (such as geopolymer) [84,85]. Apart from this environmental benefit, these natural or industrial waste-derived, cement-free alternatives also exhibit high economic viability for large-scale soil remediation with a comparable or even reduced cost compared with Portland cement [86].

Sustainable solidification also involves recycling of properly treated soil. Such re-use strategies avoid the high energy costs associated with off-site transportation and landfilling and offset the economic cost and environmental burden of long-haul importation of raw construction materials [87]. For instance, strongly solidified contaminated soil with high mechanical strength can be reused as artificial aggregate for roadway subgrade [88]. A case study showed that one such treatment and re-use scenario reduced the life cycle greenhouse gas emissions by more than a third (35%), and reduced life cycle human toxicity impact by nearly two thirds (65%) in comparison with dig & haul remediation. Moreover, if fly-ash based green cement is used to replace Portland cement, the average life cycle environmental impact could be further reduced by 40% (ref [88]).

The stabilization part of S/S mainly uses lime, phosphate, and other alkaline materials for the chemical sorption and precipitation of contaminants within the soil matrix without improving soil's mechanical strength [89]. Therefore, the stabilized soil can be reused for plant growth. However, soils treated by these conventional stabilization agents may suffer from degraded soil health, productivity, and biodiversity due to high disturbance to the physicochemical properties such as aggregation and water penetration [90], and decreased carbon stability [91]. The overuse of phosphate for soil amendment also causes an irreversible loss of terrestrial phosphorus stock [92].

A series of novel stabilization materials have been proposed, including layered double hydroxides (LDHs) [93] and biochar composites [94]. Biochar is particularly promising for sustainable stabilization because it offers lower life cycle environmental impact from different aspects (Supplementary Table 1). Firstly, it is a waste-derived biosorbent that immobilizes a wide range of pollutants, both organic and inorganic, via its porous structure, large surface area, and abundant functional groups [95]. Moreover, biochar is carbon negative, which is because the carbon content of biochar can be highly stable, with reported half-lives ($t_{1/2}$) of >1000 years, thus offering high potential for in-ground carbon sequestration [96] (Fig. 3a). Furthermore, biochar can concurrently improve soil health due to enhancing effects on soil fertility, aggregate stability, and soil organic matter [97]. Apart from soil carbon sequestration, biochar also improves other ecosystem services including reduced nitrogen leaching, reduced surface runoff, increased soil biodiversity, and enhanced water availability [98]. Social acceptance of biochar's promise as a soil amendment has also increased much, in particular for developing countries like China and India [99,100]. To assure the economic sustainability, biomass recovery and biochar pyrolysis systems should be established in a closed-loop manner [101].

Sustainable immobilization still bears the common problem of all immobilization techniques, in that contaminant substances are entrained within the treated material, in this case artificial aggregate, which means that long-term risk needs to be properly monitored and managed using science-informed guidelines and standard protocols. When applying re-use strategies, it should be aware that some practitioners may exploit the circular economy principle and unintentionally spread contaminants to a larger space to be dealt with by the next generation [102].

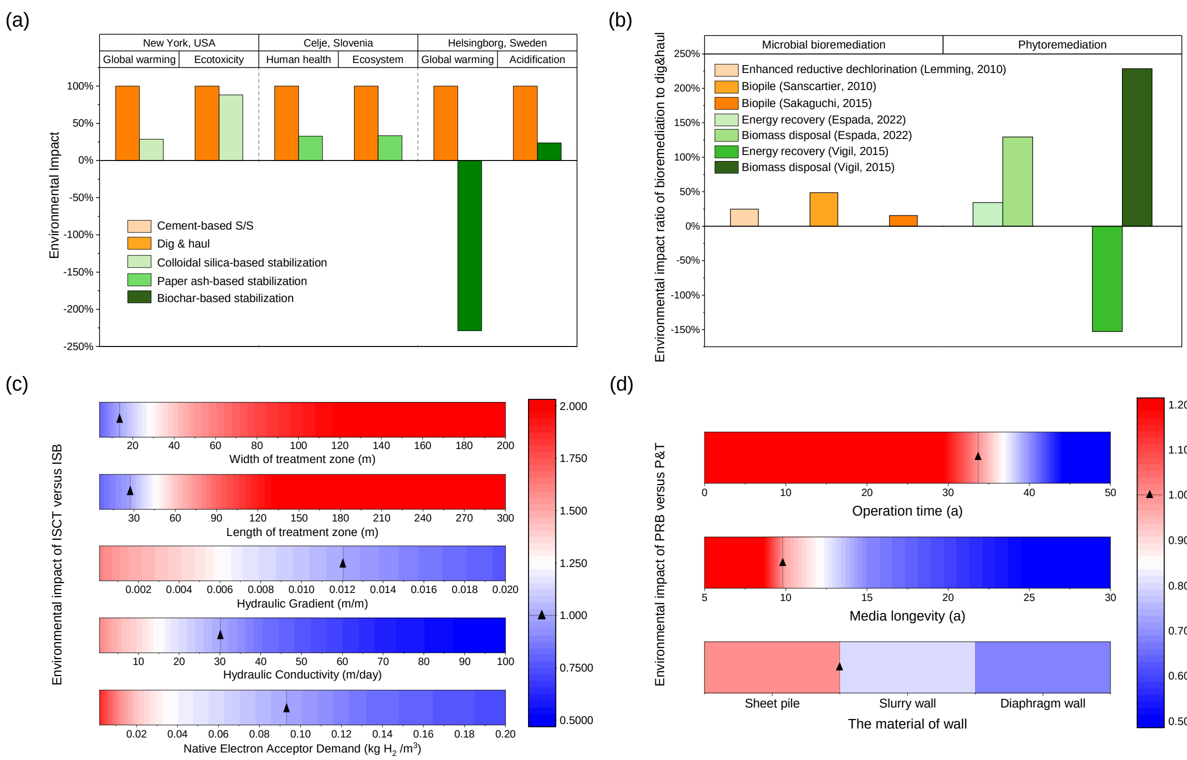


Fig. 3. Comparing the life cycle environmental impact between sustainable and traditional remediation technologies: a| the environmental impact of sustainable immobilization in comparison with dig & haul and conventional cement-based S/S, values were obtained via life cycle impact assessment for specific cases in New York, USA [103], Helsingborg, Sweden [104], and Celje, Slovenia [105]. b| the environmental impact of microbial bioremediation or phytoremediation in comparison with that of dig & haul in specific cases, values were calculated via life cycle impact assessment of five cases [45,106-109]; c| the environmental impact of in-situ chemical treatment (ISCT) in comparison with in-situ bioremediation (ISB) under a range of site characteristics, including width of treatment zone, length of treatment zone, hydraulic gradient, hydraulic conductivity, and native electron acceptor demand [110]; d| the environmental impact of permeable reactive barrier in comparison with pump & treat under different operation time, media longevity, and wall material compositions [111,112].

Sustainable remediation technologies render significantly lower life cycle environmental impact than traditional remediation technologies

3.2 Low-impact bioremediation.

Bioremediation is a green remediation approach that relies upon the ability of certain living organisms, including species of plants, bacteria, fungi, or soil animals, to remove contaminants in soil or groundwater. In this section phytoremediation that uses plants to remove or stabilize contaminants, and microbial bioremediation that uses microorganisms to degrade contaminants are discussed (Supplementary Fig. 1, Supplementary Table 1).

Phytoremediation is a widely explored soil remediation technique involving the use of plants to extract (phytoextraction), stabilize (phytostabilization), degrade (phytodegradation and rhizoremediation), or volatilize (phytovolatilization) contaminants [113]. A major benefit of phytoremediation is that it improves the ecosystem service of the originally degraded soil. Roots of plants used for phytoremediation prevents soil erosion and promotes aggregation [114]. Exudates of plants further stimulate the growth of microbes including plant-growth promoting bacteria (PGPB), thus achieving higher remediation efficiency, while simultaneously increasing soil biodiversity [115].

Among these techniques, phytoextraction has been extensively used as a gentle remediation option (GPO) for the remediation of slightly to moderately polluted agricultural soil systems [116]. For higher levels of contamination encountered at brownfield sites, the addition of mobilizing reagents to the contaminated soil may enhance phytoremediation performance [117]. More efficient phytoremediation technologies are under development based on new molecular mechanisms of plant-specific detoxification pathways and genetic modification [118,119]. It is notable that the bioremediation effect of plants is limited within the rhizosphere, which also makes it hard to use plants alone to remediate brownfields whose contaminants usually reach much deeper. Instead, phytoextraction can be used as a “polishing step” with high social acceptance due to improved aesthetics and created greenspace for leisure and entertainment, thus combining remediation with redevelopment in a natural manner [120]. Another promising technique is phytostabilization, which uses the specific metabolites from roots and/or rhizosphere microorganisms to decrease the solubility and mobility of contaminants [121]. Although this approach only reduces the mobility of contaminants without necessarily removing them, it does not generate contaminated secondary waste that needs further treatment [121]. It is suited for the remediation of large brownfields which are mildly contaminated by heavy metals [113]. Nevertheless, the long-term effectiveness of this technique should be further examined [113].

In-situ microbial bioremediation has also drawn wide attention, particularly for the remediation of groundwater contaminated by chlorinated solvents [122]. Microbial bioremediation of groundwater has the advantage of addressing the “back diffusion” problem better than traditional groundwater remediation techniques such as pump & treat [123] (Supplementary Table 1), which is a problem that has resulted in rebound, tailing, and ultimately the failure of many traditional remedial systems [124]. Researchers are also exploring innovative microbial bioremediation methods to treat recalcitrant and emerging pollutants such as PFOA/PFOS and antibiotics [125,126], as well as to enhance treatment efficiency for inhibitory comingled pollutants [127]. The rate of microbial biodegradation of pollutants is often limited due to low microbial quantity and activity, insufficient nutrients, and the oxidation-reduction potential (ORP) of the subsurface environment, amongst other factors. In this situation, bioremediation is usually enhanced by biostimulation and bioaugmentation. In biostimulation, the incorporation of certain amendments will stimulate naturally existing microorganisms to biodegrade pollutants at a faster rate. For example, injecting substrates, like vegetable oil, into groundwater provides a slow release of electron donors that render a favorable ORP condition and, thus, enables effective enhanced biodegradation over a long period [128]. Activated carbon also can be injected into the subsurface in order to retain chlorinated solvents for enhanced biodegradation [129]. In bioaugmentation, exogenous degrading microbial communities known to be effective for degrading certain types of contaminant are introduced to enrich the biodegradation potential of the microbial taxa within the contaminated groundwater, thereby accelerating the biodegradation process.

The sustainability of phytoremediation and microbial bioremediation lie in the high economic viability (Fig. 2c), high social acceptance, and low life cycle environmental impact. As an in-situ remediation method bioremediation offers a lower economic burden in comparison with most other traditional ex-situ remediation methods (Fig. 2c) [130]. Surveys have also shown that the general public perceive bioremediation to be more environmentally friendly and, therefore, it has high social acceptance [131]. The life cycle environmental impact of bioremediation is usually much lower than that of physical or chemical treatment methods. For example, LCA studies have shown that microbial bioremediation reduced global warming potential by 50%~90% in comparison with dig & haul remediation; and phytoremediation reduced environmental impact by up to 250% (Fig. 3b). A case study in Denmark revealed that in-situ bioremediation was the only remedial option that could out-perform the no-action option, with life cycle carcinogenic human toxicity impact 76% lower than thermal desorption and 92% lower than dig & haul [45].

However, both phytoremediation and microbial bioremediation still face various challenges, especially related to the long time taken to achieve remediation goals. For phytoremediation, it can render higher carbon footprints and overall environmental footprints than other approaches without energy recovery (Fig. 3b) [108,109]. A proper disposal of harvested biomass enriched with toxic elements is also required to assure the environmental sustainability (Fig. 3b), which may be costly [132]. The combination of phytoremediation with redevelopment, such as nature-based solution or sustainable energy harvesting, renders a promising direction (see next section). Microbial bioremediation is widely used in the US, but it has seen extremely low adoption rates in many countries, such as China, where the remediation market is development driven and requires faster-paced methods [102]. Moreover, bioremediation can potentially generate toxic by-products. For instance, reductive dechlorination of chlorinated ethene (such as TCE and PCE) involves the toxic substance vinyl chloride as an intermediary daughter product [122]. Therefore, it is important to develop specialized bioremediation treatment cultures, sequential treatment strategies, and complete biodegradation pathways toward non-toxic end products and at a rapid pace and controllable manner [133].

3.3 Novel in-situ chemical treatment.

In-situ chemical treatment of contaminated groundwater involves either in-situ chemical oxidation (ISCO) or in-situ chemical reduction (ISCR). Because in-situ treatment does not involve excavation, it tends to be more cost effective than pump & treat approach and is less likely to create unintended exposure scenarios or create dust and odor nuisance for local residents (Supplementary Fig. 1). In-situ chemical treatment has become one of the most widely used in-situ remediation approaches [35] because it can render more rapid cleanup times than other in-situ technologies.

However, evidence is mounting that traditional in-situ chemical treatment strategies could possess higher environmental impacts. The manufacture of chemical treatment reactants can cause substantial secondary environmental impacts beyond the site boundary [44,134]. When comparing the life cycle global warming potential for a diesel-contaminated groundwater remediation project, ISCO was found to render much higher impact than alternative technologies pump & treat and bio-sparging [44]. Moreover, ISCO needs to be applied with caution because it can lead to potentially severe secondary water quality issues, thus increasing the overall environmental impact. For example, it can cause the conversion of Cr(III) to highly toxic Cr(VI), and formation of manganese dioxide precipitates that clog aquifer pore space [22]. Nevertheless, under certain specific site characteristics, in-situ chemical treatment can provide lower environmental impact than other technologies [110], particularly at sites with relatively small contaminant source zones and a relatively large hydraulic gradient or hydraulic conductivity, or abundant native electron acceptors for chlorinated solvent sites (Fig. 3c).

Scientific advances are needed to render in-situ chemical treatment more effective and sustainable. Firstly, remediation materials must have greater treatment efficiency so that a smaller amount of materials need to be fabricated for a brownfield remedy, thus achieving lower environmental and economic impacts simultaneously. It can be accomplished via the adoption of decorated nanomaterials with high selectivity towards target contaminants. For example, the commercialization of nanoscale zero-valent iron (nZVI) has significantly advanced the efficiency of chlorinated solvent removal compared to traditional granulated ZVI [135]. The benefit are still being realized showing that nZVI renders high treatment efficiency for residual non-aqueous liquid (NAPL) via both in-situ abiotic degradation and pore-scale remobilization induced by gaseous products [136]. The nZVI technology has been advanced further by sulfidization, which provides both rapid dechlorination and defluorination of recalcitrant and emerging pollutants [137]. The addition of sulfur facilitates chemical reduction by atomic hydrogen and hinders hydrogen recombination. It renders treatments that are contaminant-specific, selective against the background reaction of water reduction and, overall, more efficient [138]. For example, FeS-coated nZVI has been shown to degrade trichloroethene 60 times faster than ZVI [139].

Secondly, innovative material design and material delivery need to be developed to maintain long-term treatment efficiency while avoiding or reducing secondary water quality issues. In this way the problem of back diffusion could be effectively mitigated (Supplementary Table 1). For example, sulfurized nZVI stabilized with carboxymethyl cellulose (CMC) can effectively treat a mixture of chlorinated solvents without accumulation of toxic byproducts [140]. Thermally activated peroxydisulfate ISCO helps desorption/dissolution of organic contaminants and efficient activation of oxidants, but has suffered from short lifetime of peroxydisulfate. Peroxide stabilizers have been developed that increase the longevity of thermally activated peroxydisulfate for enhanced ISCO remediation [141]. Controlled release mechanisms have also been explored as a way to offer long-term treatment of contaminated groundwater and avoid rebound issues [142].

Thirdly, green synthesis approaches need to be developed to produce in-situ chemical treatment reactant in a more environmentally friendly way [143]. Utilization of safer chemicals and solvents and maximization of atom economy, which are principles of green chemistry, serve as the key to lower the cradle-to-gate environmental footprint of material manufacturing [144]. Materials derived from biological waste hold great promise in this research direction [145].

3.4 Innovative passive barrier systems.

Complex hydrogeological conditions encountered at some brownfield sites make it infeasible to reduce pollutant concentrations in groundwater to risk-based target levels within a reasonable time frame [6]. It is therefore necessary to manage the risk by controlling the migration of contaminants. Permeable reactive barrier (PRB) systems rely on in-ground impermeable barriers to direct contaminated groundwater to flow through a permeable reactive zone, which removes contaminants by adsorption, precipitation, or degradation (Supplementary Table 1) [146]. The long-term effectiveness of PRB systems assure its environmental sustainability (Fig. 3d). For instance, for PRB systems based on adsorption using granular activated carbon (GAC), PRBs offer lower global warming impact than pump & treat if the operation time is relatively long and constructed without steel sheet piles (Fig. 3d) [111]. For a PRB system based on degradation by ZVI, PRB renders lower global warming impact than pump & treat as long as ZVI longevity exceeds 10 years [112] (Fig. 3d). The life cycle environmental impact of PRB systems is influenced by groundwater constituents, such as dissolved organic matter, due to their interaction with reactive media causing surface passivation and flow path blockage [147]. A retrospective assessment on one of the earliest installed PRB systems indicated that ZVI had remained biogeochemically active for over 20 years [148], suggesting that passive barriers can be effective for long-term risk management.

The future development of PRB systems lies in novel functional materials and processes that render enhanced removal efficiency, high selectivity, and extended longevity. In this context both environmental and economic sustainability can be improved. Such materials and processes should be carefully designed to exploit multiple and complementary functionalities. For example, an innovative nanomaterial was developed for use in barrier systems using chemically modified lignocellulosic biomass, achieving high adsorption capacity due to their amphiphilic properties, while enabling subsequent fungal-based biodegradation of PFOA/PFOS contaminants [149]. This newly designed material renders a 97% reduction in net CO_2 emission compared to GAC-based treatment. The affinity of pyridinium-based anion nanotraps was manipulated to enable long-term segregation of radionuclide contamination under extreme acidic and basic conditions [150]. In another case, an in-situ ultrasonic reactor was established as an innovative passive barrier, which could reduce CO_2 emission by 91%

over a 30-year period in comparison with pump & treat of PFAS contaminated groundwater [151]. These innovative materials and processes have potential in creating a new generation of PRB that significantly increases the overall net benefit of remediation.

A common theme of the four sustainable remediation strategies discussed above is technological innovation which reduces material and energy input, as well as minimizing waste and secondary toxic byproducts, while enhancing economic vitality and social acceptance. Traditional remediation agents are replaced with waste-derived, green-synthesized, or natural materials, or living organisms, thus lowering the life cycle environmental impacts and economic costs associated with material fabrication. Moreover, gentle remediation options also improve soil health, preserve biodiversity, and restore ecosystem services, creating additional aesthetic values with higher social acceptance as compared with traditional strategies. Extending the longevity of remediation also minimizes the risks associated with contaminant rebound and migration, thus reducing the environmental and economic impacts in the long-term.

4. Integrate remediation and redevelopment

Remediation represents one crucial step in BRR; however, it should co-occur with redevelopment to maximize sustainability gains. Traditionally remediation and redevelopment are often conducted in separate phases, creating barriers for each other's optimization. Decisions are made based on narrow values and only reflect a portion of stakeholders at each phase. This conventional mode for BRR has caused a huge missed opportunity for synergies between remediation and redevelopment. To align sustainable remediation with sustainable redevelopment, it is imperative to incorporate various normative sustainable development principles, as well as to integrate diverse needs of different user groups [14,41]. Existing studies have shed light on two promising strategies implemented at brownfield sites: nature based solutions (NBS) and renewable energy generation, both of which are now discussed (Table 1).

Table 1. Environmental, social, and economic benefits of sustainable strategies integrating remediation with redevelopment

Sustainable strategies	Environmental benefits	Economic benefits	Social benefits	Disadvantages
Nature based solutions				
Construction of large urban park	Improved soil health; soil erosion control; carbon sequestration; reduce heat island effect; enhance flood control; improved ecosystem [152,153]	Low cost; increase property value in neighborhood [72,154]	Improve local livability; enhance hobbies and leisure activities; promote social cohesion; aesthetic value; improve spiritual health [152,154]	Occupation of large precious urban land; require long-term monitoring and financial arrangement [72,120]
Green and blue infrastructures incorporated into site landscape	Carbon storage by woody biomass; regulating microclimate; noise attenuation; healthy ecosystem [120,152]	Encourage inner city investment; enhanced flood control [154,155]	Aesthetic value; increase human-environment connection; improve spiritual health; stigma reduction [152,154]	Financial and administrative challenge in long-term operation and maintenance; slow contaminant removal rate [120,156]
Conversion to industrial heritage park	Reduce environmental footprint embedded in construction; mitigate heat island effect; provide local habitat for wildlife [120,157]	Utilize existing infrastructure; stimulate spending; increase tax revenue [154]	Heritage protection; enhance cultural diversity; encourage hobbies and leisure activities; promote educational activities; improve spiritual health [154,158]	Controversy about aesthetic value; potential health and safety hazard [159]
Sustainable energy generation				
Energy biomass	Reduce fossil fuel consumption and CO_2 emission; restore degraded land; reduce erosion [108,109]	Render economic competitiveness for phytoremediation [80]	Reduce competition with food production; enhance fuel price stability [160]	Not suitable for heavy contamination; potential contamination transfer to biofuel; air pollution; substantial water usage [161,162]

Solar power	Conserve greenfield; improve air quality; [59]	Reduce development cost; electricity cost saving; avoid zoning constraints; increase tax revenue; close to user and reduce transmission requirement [59,79]	Create jobs; shorten development timeframe [59,163]	Require sunny climatic condition; need appropriate site topography [164,165]
Wind power	Conserve greenfield; improve air quality [59]	Reduce development cost; avoid zoning constraints; increase tax revenue; close to user and reduce transmission requirement [59,79]	Employment benefit; aesthetic value; improve spiritual health [163,166]	Require windy climatic condition [164]
Heat pump	Reduce fossil fuel or electricity consumption; lower carbon footprint [167]	Low operation cost; short payback time [81,168]	Fuel poverty reduction; reduce energy bill for end users [169]	Technological robustness still need proof; high capital cost [168,170]

4.1 Nature based solutions

Brownfield sites are refuges for microorganisms, soil fauna, plants, and birds [171,172]. Traditional brownfield remediation and redevelopment often lead to losses of biodiversity [172,173]. Nature based solutions refer to BRR strategies that are inspired and supported by nature, simultaneously providing human well-being and biodiversity benefits [174]. They offer superior effect in BRR for improved ecosystem services include carbon sequestration, soil erosion prevention, nutrient regulation, biodiversity, aesthetic values, and air quality regulation [175,176]. Three most commonly used NBS for BRR are discussed here: conversion to urban parks, green and blue infrastructure, and conversion to industrial heritage parks, as they provide a diverse range of environmental, social, and economic benefits (Fig. 2d, Table 1).

Construction of large urban greenspace on potentially contaminated land represents a soft-use of brownfield that avoids sealing soil and maintains or enhances its biological function, serving as a wildlife habitat and bringing amenity and recreational value [59,120]. In Merseyside, UK, a 28-ha landfill site was converted to an urban park, which provides visitors with a scenic waterfront and a variety of walks. A qualitative multi-criteria analysis showed that this NBS had reduced environmental, economic, and social impact scores by 33%, 33%, and 50%, respectively [72]. In Beijing, China, a 173-ha petrochemical site was converted into a major urban park. Environmental monitoring data showed that the risk from soil and groundwater contamination at the park is low due to natural attenuation and that local biodiversity is greatly improved [153]. It is notable that it is not always possible to install a vegetation cover directly on a degraded brownfield. In this case soil construction serves as a promising assisting strategy for the ecological restoration, where fertile surficial soil layers are established with green waste compost, papermill sludge, crushed brick, rubble and other urban or industrial wastes [177,178]. Low environmental impact of this pedological engineering strategy lies in high carbon storage capacity of the artificial soil layer, as well as its potential as an alternative solution to waste landfilling [179,180].

Green and blue infrastructure (GBI), such as green landscaping and constructed wetlands, can be an attractive NBS for addressing low concentrations of pollutants in soil, groundwater and storm runoff at brownfields. In California, USA, eucalyptus and willow trees were incorporated into a brownfield landscape for the effective removal of organic pollutants via phytovolatilization [156]. In Brisbane, Australia, a constructed wetland was used at a brownfield site to treat contaminated surface runoff, which was reused for irrigation [181]. In Oslo, Norway, buried storm water pipes on brownfield land were converted into open watercourses, which reduced potential leaching of toxic substances from landfill sites, and provided new recreational space for urban residents [155]. These NBS systems are incorporated into urban landscape, rendering a variety of benefits, including aesthetic improvement, noise and dust reduction, and CO_2 sequestration [152]. Moreover, native plants can be used in GBI to further reduce the life cycle environmental impact in comparison with conventional brownfield landscapes [182].

Conversion of brownfield sites into industrial heritage parks represents another promising strategy. It can provide a recreational destination, while fulfilling the purpose of heritage protection and enhancing cultural diversity [158]. In Duisburg, Germany, a 20-ha brownfield site was developed into a heritage park which highlights industrialization history [120]. In Beijing, China, a 70-ha Shougang Industrial Heritage Park was built within one of China's largest steelworks, which became a major venue for the 2022 Winter Olympic games to enhance the sustainability of this mega-event [159].

Despite the multi-faceted benefits of NBS, there are also obstacles for their adoption. Plants can emit biological VOCs and toxic pollens, posing a potential public health risk [152]. This obstacle requires careful selection of plant species to mitigate. Nature based solutions also require continuous investment in long-term risk management and monitoring, which can sway private investment from choosing such strategies [120]. Financial arrangements may be established among the liability owner, land owner, and management entity to address such issues [183].

4.2 Renewable energy generation

Sustainable energy generation can serve as a catalyst for the integration of remediation and redevelopment at brownfield sites. The ongoing shift toward carbon neutrality and net zero places a strong demand for renewable energy, including biofuels, solar, wind, and geothermal energy (Fig. 2d) [184]. However, it is often hindered by local zoning requirements due to land constraints [79].

Derelict brownfield sites should be prioritized as suitable locations for rapid deployment of such sustainable energy projects by local governments [164]. Wind and solar energy on brownfields is attractive for developers because it can reduce the development project cycle due to streamlined permitting and zoning and improved project economics [163]. In New York, USA, 14 wind turbines were built on a 12-ha former steel mill site to generate electricity (34 MW), bringing green energy and economic revival to the local community [166]. In Massachusetts, USA, solar panels (3 MW) were installed on a 5-ha former landfill site, as part of helping the city to reach its 100% renewable energy goal [165]. In Michigan, USA, it was estimated that the total wind and solar energy potential at its brownfield sites was over 5,800 MW, which is equivalent to 43% of the entire state's residential electricity consumption [79].

The growing of plants for energy biomass on marginal land, such as brownfield sites, holds great promise [185]. A variety of plant species may be used to remove or stabilize soil pollutants while also supplying a useful end product such as bioethanol, biodiesel, and charcoal or biochar [186], which can render substantial life cycle environmental benefits for phytoremediation [108]. In Spain, a phytoremediation system coupled with bioenergy harvesting was found to reduce global warming potential, acidification potential, and eco-toxicity potential by 80%, 83%, and 91%, respectively, in comparison with a biomass disposal option [109]. To further strengthen the feasibility and sustainability of such systems, more effort is required to enhance water use efficiency, biodiversity conservation, avoiding pollution transfer, and stakeholder engagement [161,162].

Aquifer thermal energy storage (ATES) can be integrated into the bioremediation of contaminated soil and groundwater to render sustainability synergies [167]. The temperature of shallow groundwater is relatively constant year-round; therefore, it can be extracted and re-circulated for space heating in winter and cooling in summer. The improved flow condition and rising groundwater temperature in ATES can be used to enhance in-situ biodegradation [170]. When compared with conventional separate operations, this sustainable integrated system can reduce life cycle greenhouse gas emission by 66% (ref [167]). This technology has been proved with a field demonstration; however, further technological advancement is required to address several challenges for wider commercial application. In particular, detachment of microbial biomass, fluctuation in subsurface redox condition, and chemical and biological clogging need to be mitigated [170].

5. Resilience in a rapidly changing world

Sustainability of BRR is not only affected by aforementioned issues, but also challenged by global changes in the Earth system. Alterations in geophysical conditions, such as flooding and sea level rise, pose a challenge to the resilience of remediation systems. Millions of people live in the vicinity of contaminated sites who are increasingly vulnerable to flooding and sea-level rise driven by climate change [183]. Inundation and infiltration at contaminated sites could facilitate the spread of pollutants due to surface runoff and contaminated groundwater migration [187]. In this context, ecosystem service of remediated land must be improved to build resilience against these changes. In the face of these changing conditions, passive treatment technologies like PRB and tree-based hydraulic control systems require proof of resilience [156,187]. 100-year modeling under various climate change scenarios suggested that phytoremediation at a coastal brownfield site had good resilience to rising temperature, climatic water deficit, and moderate sea-level rise; but under extreme sea-level rise scenario, the complex system would pass a tipping point that drastically increased the environmental risk [156].

Site remediation also needs to consider changing social conditions. For instance, during historical urbanization, many urban rivers were converted to underground watercourses; for example, Denmark and Sweden have 15% and 20% river lengths lost to pipes, respectively [188]. For underground pipes located in brownfield land, increased precipitation levels due to climate change is a high risk. Leaks and overflow from aged pipes can result in increased leaching of soil pollutants, threatening both groundwater and adjacent surface water [155]. On the other hand, scientific discovery and the continuous improvement of living standards can lead to more robust public health standards and reduced acceptable risk level. For example, in the USA until 2012, the childhood blood lead level of concern was >10 μg/dL. The CDC now uses a more stringent blood lead reference value of 3.5 μg/dL. Such changes in acceptable risk level could in turn result in repeated risk-based remediation and impose substantial costs [15]. Another grand challenge is emerging contaminants that come to spotlight based on new scientific findings. Contaminants like PFAS was not a target of remediation 10 years ago, but it is becoming a brownfield site constituent of concern (COC) nowadays in many countries; microplastic and nanoplastics are not a brownfield COC for now, but based on an increasing body of evidence showing their prevalence, toxicity, and exposure pathways, they may become future brownfield COC.

Hence sustainable remediation must be inherently resilient to these changing geophysical (such as climate change and pollution migration) and social conditions (such as more stringent regulatory standards and new development needs) (Fig. 4). Remedial systems need to be resistant to future changes; and as changes become so significant that intervention is inevitable, existing remedial systems must be designed with high levels of adaptability to avoid double effort [15]. Resilient remediation strategies might require higher initial investment, but can result in better life cycle return of environmental and social benefits (Fig. 4). Landscape design can also greatly improve BRR resilience by taking into account the evolving scientific understanding of exposure risks and changing public policies [189]. Physical barriers such as capping systems can help to mitigate risks from flooding and erosion, rendering higher resilience to changes in geophysical conditions (Fig. 4). For instance, a contaminated soil capping system at a site in Washington, USA, was doubled in size to provide greater resilience to more frequent severe storms [183]. Converting underground storm pipes into surface water courses, as part of a NBS on brownfield land, is one way to adapt to extreme climate events, because above ground river system render additional flood pathways and infiltration capability [155]. Woody plants used in phytoremediation can also help mitigate flooding risk in certain locations [152]. For brownfield sites with residual contaminants and post-remediation management, it is necessary to conduct more frequent groundwater monitoring during precipitation and drought periods because contaminant concentrations are directly affected by these processes [187].

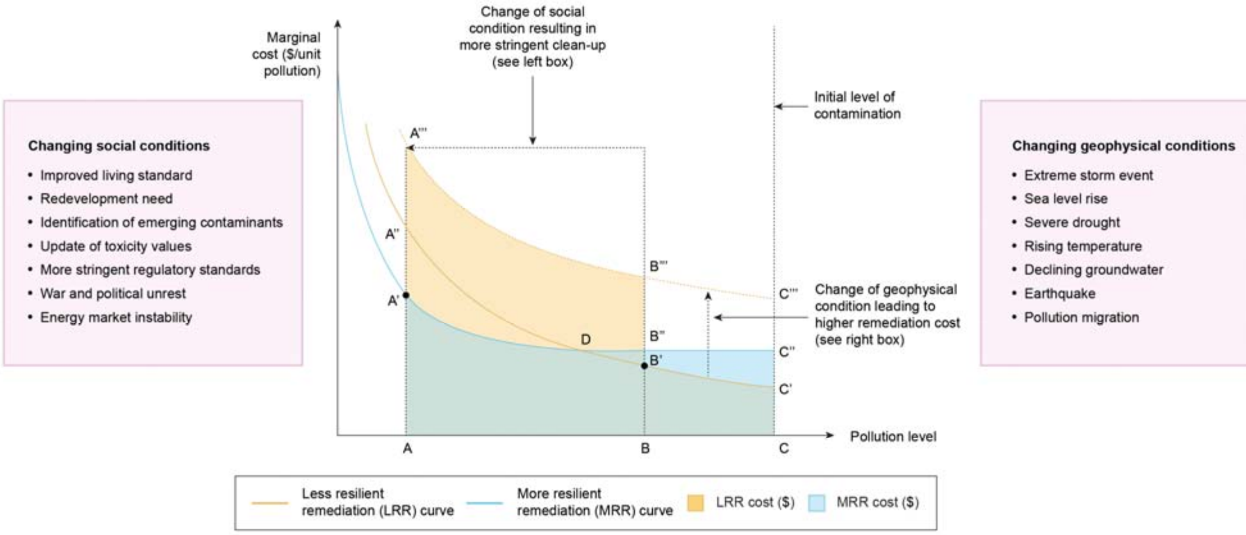


Fig. 4. Resilience of sustainable remediation approaches under changing social (left box) and geophysical conditions (right box). Resilience is achieved via two aspects: (1) more resistant to change in geophysical conditions, such as climate change and pollution migration; and (2) imposing lower marginal cost if more stringent cleanup is needed due to social change, such as improved living standard and redevelopment need. A more resilient remediation (MRR) strategy might initially render higher cost (the area surrounded by BCC''B'') than a less resilient remediation (LRR) strategy (BCC'B'); however, MRR cost over the long term (ACC''A') can be much lower than LRR cost (ACC'B'B'''A'''). A resilient remediation strategy is more resistant to changes in geophysical conditions and social conditions. Figure modified, with permission, from [15].

6. Summary and future perspectives

Sustainable remediation offers multi-faceted opportunities to alleviate challenges posed by land contamination. It aims to internalize the indirect environmental costs, and to maximize wider social and economic benefits. Sustainable immobilization, low-impact bioremediation, novel in-situ chemical treatment, and innovative passive barriers are promising remediation strategies; moreover, the integration of sustainable remediation with redevelopment can further maximize environmental, social and economic benefits. However, several challenges still remain for sustainable BRR, where future research efforts are much needed.

The first challenge is how to reconcile different value considerations by various stakeholders. Many environmental, social, and economic impacts are external to the traditional financial model that governs BRR decision-making processes. The direct and indirect impacts associated with BRR has meant the economic value of brownfield is often discounted. Therefore, broader recognition of the socioeconomic and environmental benefits in the context of sustainable development is much needed. It requires a concerted action of developers and other stakeholders [14]. Future research studies must capture both tangible and intangible value considerations, ideally covering both attributional and consequential impacts. Local stakeholder engagement is essential in balancing the trade-offs and different priorities. Therefore, it is important to conduct comprehensive assessment in a quantitative manner to render more convincing results. Sustainability can only become relevant in decision making when the indirect costs are quantifiably measurable and fully transparent. Moreover, social impact assessment is often lacking or conducted using subjective methods [41], which can be difficult for various stakeholders with distinctive disciplinary backgrounds to reach consensus. Future studies need to develop objective and quantitative assessment methods that can aggregate a wide range of value considerations, thus making the results visible to policy makers and practical decision makers.

The second challenge is how to better align sustainable remediation with the net zero transition. Carbon neutrality, which has become a new mandate for the entire economy, will undoubtedly influence the adoption of sustainable remediation. In comparison with traditional remediation methods, sustainable remediation technologies can typically reduce the life cycle greenhouse gas emission by 50%~80% (refs [45,103,109]), and some innovative functional materials can reduce carbon footprint by over 95% (ref [149]). Biochar derived from biological waste can even be used in soil remediation to achieve negative carbon footprint. However, green remediation methods are often less efficient, requiring long periods to achieve target cleanup goals or requiring long-term post-remediation risk management. Moreover, innovative functional materials can be cost prohibitive, unless they can be synthesized on a massive scale with significantly lower cost. Both issues need to be alleviated by technology advancement and technology diffusion. On a city-level, brownfield remediation and redevelopment also offers substantial climate change mitigation because it reduces household energy consumption, commute distance, and infrastructure construction need. However, research-informed policy instruments are much needed to incentivize decision makers.

Thirdly, the integration of remediation and redevelopment requires more policy innovation and inter-disciplinary collaboration to enable wide application. Traditionally remediation and redevelopment phases have often been separated sequentially. Their integration into parallel phases can bring substantial sustainability benefits; however, existing literature on BRR often lacks a multi-disciplinary lens that can fully capture all pertaining value considerations. Moreover, the determinants of environmental, social and economic benefits are not well understood. Ethics and equality are almost never considered in the assessment tools. Remediation and revalorization of brownfields make the city sites and neighborhoods more attractive and increases land price, rents and the overall cost-of-living, thereby forcing lower-income communities to be displaced elsewhere [192]. New governance mode ought to be more inclusive and help to overcome this challenge, although the political and power aspect that is inherent within inequality issues needs to be simultaneously addressed [193]. Nature based solutions and sustainable energy systems hold huge potential, but they are encountering obstacles in deployment and market penetration. There is a strong need for research collaboration between environmental engineers and urban planners to identify smart strategies, as well as enhanced information transfer and collaboration between environmental and planning regulatory agencies to materialize the full potential [194]. When facing future uncertainties and global environmental changes, remediation systems must also be inherently resilient. By addressing these dynamic issues, sustainable brownfield remediation and redevelopment can offer a revolutionary opportunity for urban revitalization and socio-ecological transformation.

Glossary

BACK DIFFUSION

The contamination of a high permeability zone of groundwater aquifer by the diffusive transport of contaminants out of an adjacent low permeability zone.

BIOCHAR

A solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment.

BIOSTIMULATION

The addition of rate-limiting nutrients to groundwater to stimulate contaminant degradation by native microorganisms.

BIOAUGMENTATION

The addition of microorganisms to groundwater for contaminant degradation.

BROWNFIELD

Former developed sites that are derelict or underused due to potential or perceived contamination of soil and groundwater by hazardous substances.

DIG & HAUL

The excavation and off-site disposal process of contaminated soil, which require a pre-treatment procedure sometimes in order to meet land disposal restrictions.

GREENFIELD
An area of land that has not previously been developed.

HYDRAULIC CONTROL
A technique used to control the movement of contaminated groundwater.

IMPACT HOT SPOT
The category with much higher life cycle impact as compared with others.

LAYERED DOUBLE HYDROXIDES
A class of synthetic clay minerals with brucite-like cationic layers containing anions in the hydrated interlayer for charge balance.

NATURE BASED SOLUTION
Remediation strategies that are inspired and supported by nature, simultaneously providing human well-being and biodiversity benefits.

PERMEABLE REACTIVE BARRIER
A passive system for in-situ groundwater remediation, where contaminated water passes through the active material with high permeability, contaminants being sorbed or degraded.

PHYTOREMEDIATION
The use of plants to extract (phytoextraction), stabilize (phytostabilization), degrade (phytodegradation and rhizoremediation), or volatilize (phytovolatilization) contaminants either from the unsaturated soil vadose zone or groundwater.

PUMP & TREAT
An ex-situ remediation system where contaminated groundwater is pumped from the subsurface, treated above ground, and discharged.

SCENARIO ANALYSIS
Analysis of different possible situations relevant for life cycle assessment applications based on specific assumptions.

SENSITIVITY ANALYSIS
Analysis of the robustness of results and their sensitivity to uncertainty factors in life cycle assessment.

SOLIDIFICATION/STABILIZATION
A remediation technology where contaminated soil is physically bound and enclosed within a solidified matrix, or chemically reacted and immobilized by the stabilizing agent.

SUSTAINABLE REMEDIATION
Remediation strategies and technologies that maximize the net environmental, social, and economic benefits.

SYSTEM BOUNDARY
Boundaries for which processes in brownfield remediation that is included in the life cycle analysis.

THERMAL DESORPTION
A physical process designed to remove volatile contaminants from soil via heating.

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Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 42225703) and and National Key Research and Development Program of China (Grant No. 2020YFC1808000).

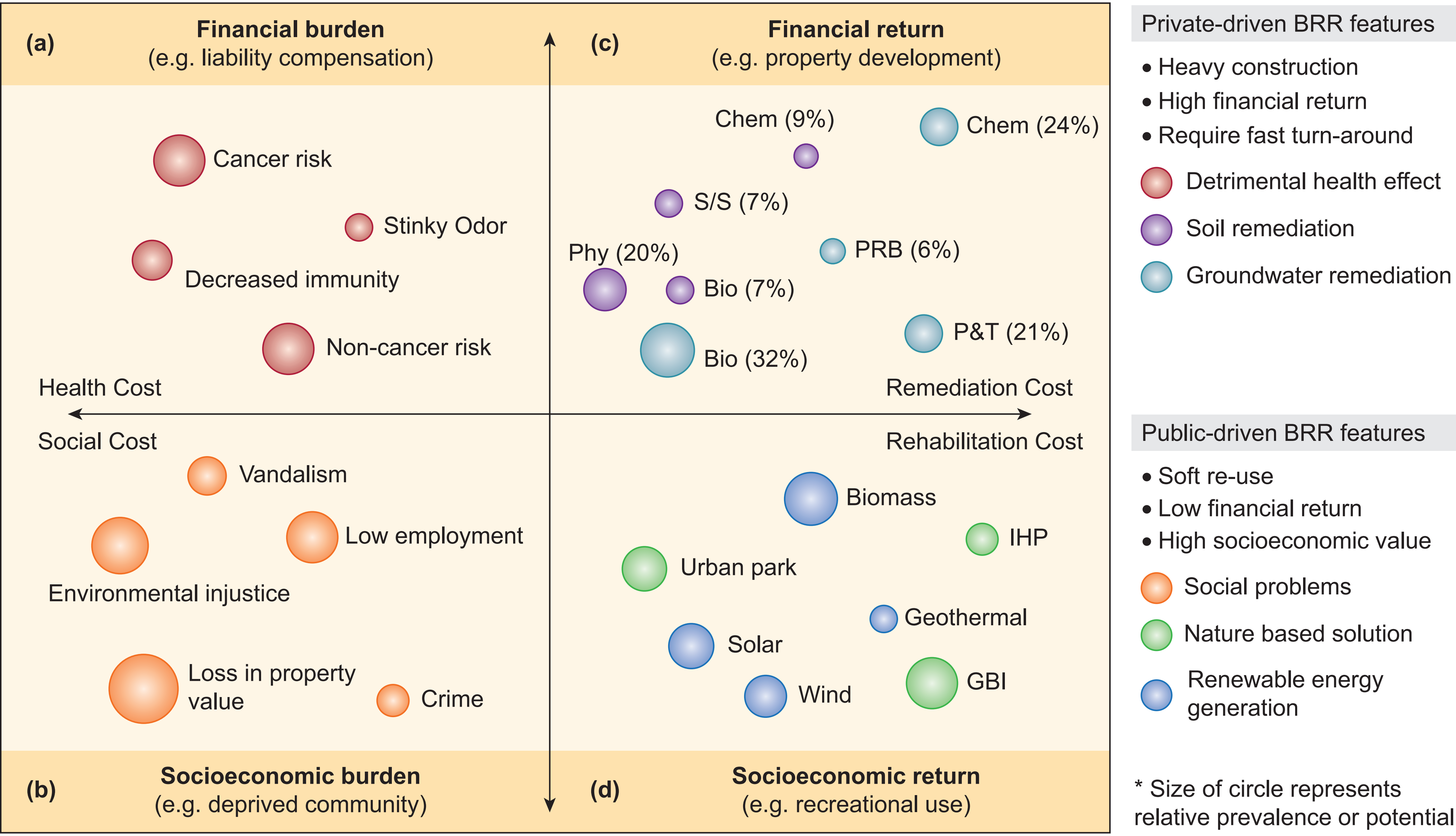
Competing interests

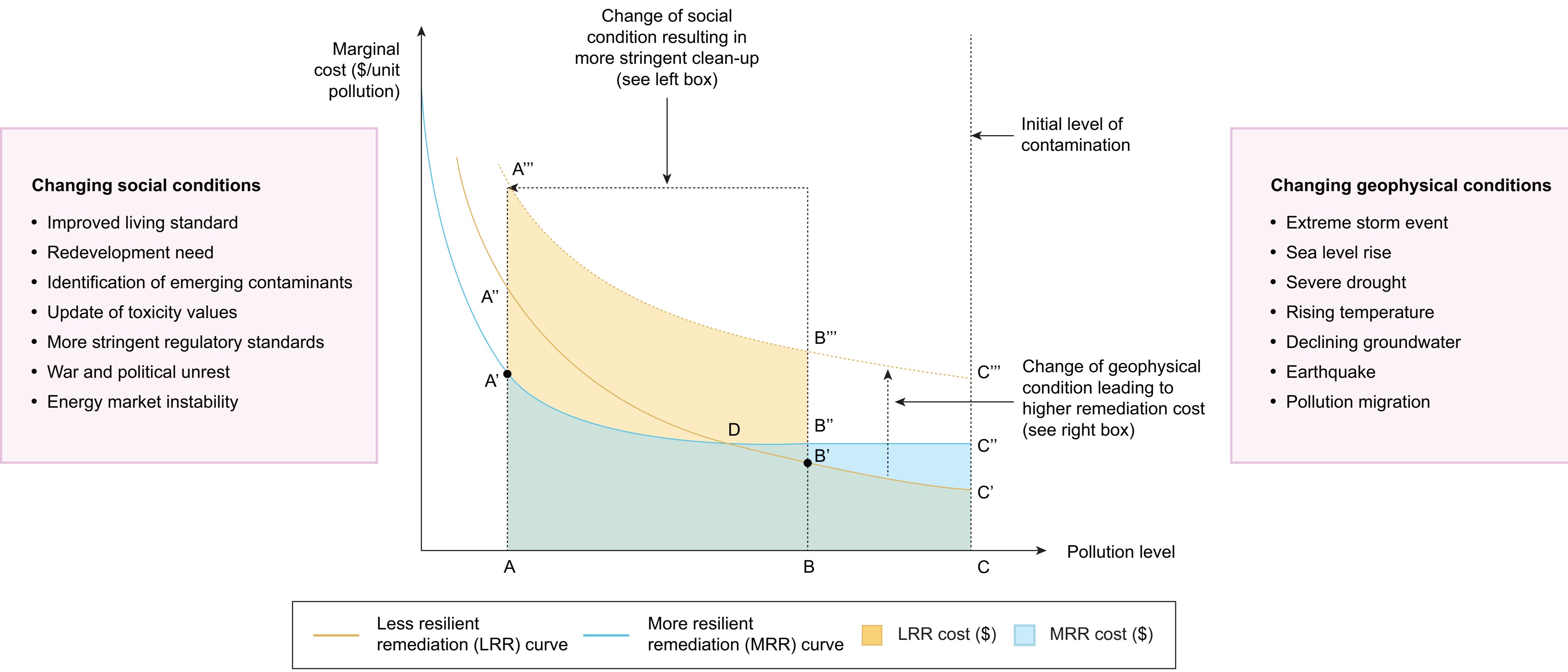
The authors declare no competing interests.

Author contributions

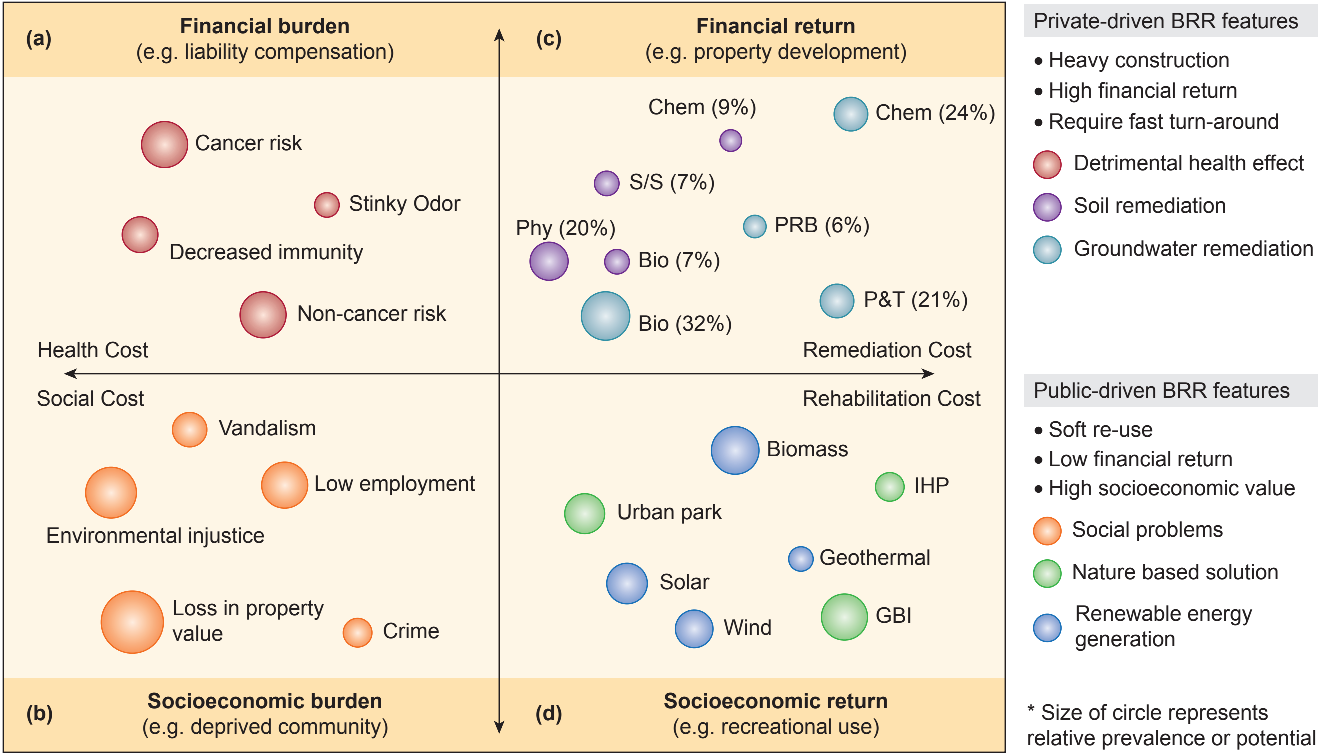
DH: conceptualization, data analysis, writing
AA: review/editing
DC: review/editing
QH: review/editing
YZ: review/editing
LW: data collection, review/editing
NK: review/editing
YSO: review/editing
DT: review/editing
NB: review/editing
JR: review/editing

Publisher's note


(a)
Financial burden
(e.g. liability compensation)
(c)
Financial return
(e.g. property development)
Cancer risk
Stinky Odor
Decreased immunity
Non-cancer risk
Chem (9%)
Chem (24%)
S/S (7%)
PRB (6%)
Phy (20%)
Bio (7%)
P&T (21%)
Bio (32%)
Health Cost
Remediation Cost
Social Cost
Rehabilitation Cost
Vandalism
Low employment
Environmental injustice
Loss in property value
Crime
Biomass
IHP
Urban park
Geothermal
Solar
Wind
GBI
(b)
Socioeconomic burden
(e.g. deprived community)
(d)
Socioeconomic return
(e.g. recreational use)
Private-driven BRR features
• Heavy construction
• High financial return
• Require fast turn-around
Detrimental health effect
Soil remediation
Groundwater remediation
Public-driven BRR features
• Soft re-use
• Low financial return
• High socioeconomic value
Social problems
Nature based solution
Renewable energy generation
* Size of circle represents relative prevalence or potential



Changing social conditions
Improved living standard
Redevelopment need
Identification of emerging contaminants
Update of toxicity values
More stringent regulatory standards
War and political unrest
Energy market instability
Marginal cost ($/unit pollution)
Change of social condition resulting in more stringent clean-up (see left box)
Initial level of contamination
A'''
A''
A'
B'''
B''
B'
C'''
C''
C'
D
Change of geophysical condition leading to higher remediation cost (see right box)
A
B
C
Pollution level
Changing geophysical conditions
Extreme storm event
Sea level rise
Severe drought
Rising temperature
Declining groundwater
Earthquake
Pollution migration
Less resilient remediation (LRR) curve
More resilient remediation (MRR) curve
LRR cost ($)
MRR cost ($)


(a)
Financial burden
(e.g. liability compensation)
(c)
Financial return
(e.g. property development)
Private-driven BRR features
• Heavy construction
• High financial return
• Require fast turn-around
Detrimental health effect
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Cancer risk
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PRB (6%)
Phy (20%)
Bio (7%)
P&T (21%)
Bio (32%)
Remediation Cost
Social Cost
Vandalism
Low employment
Environmental injustice
Loss in property value
Crime
Rehabilitation Cost
Biomass
IHP
Urban park
Geothermal
Solar
GBI
Wind
Public-driven BRR features
• Soft re-use
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Social problems
Nature based solution
Renewable energy generation
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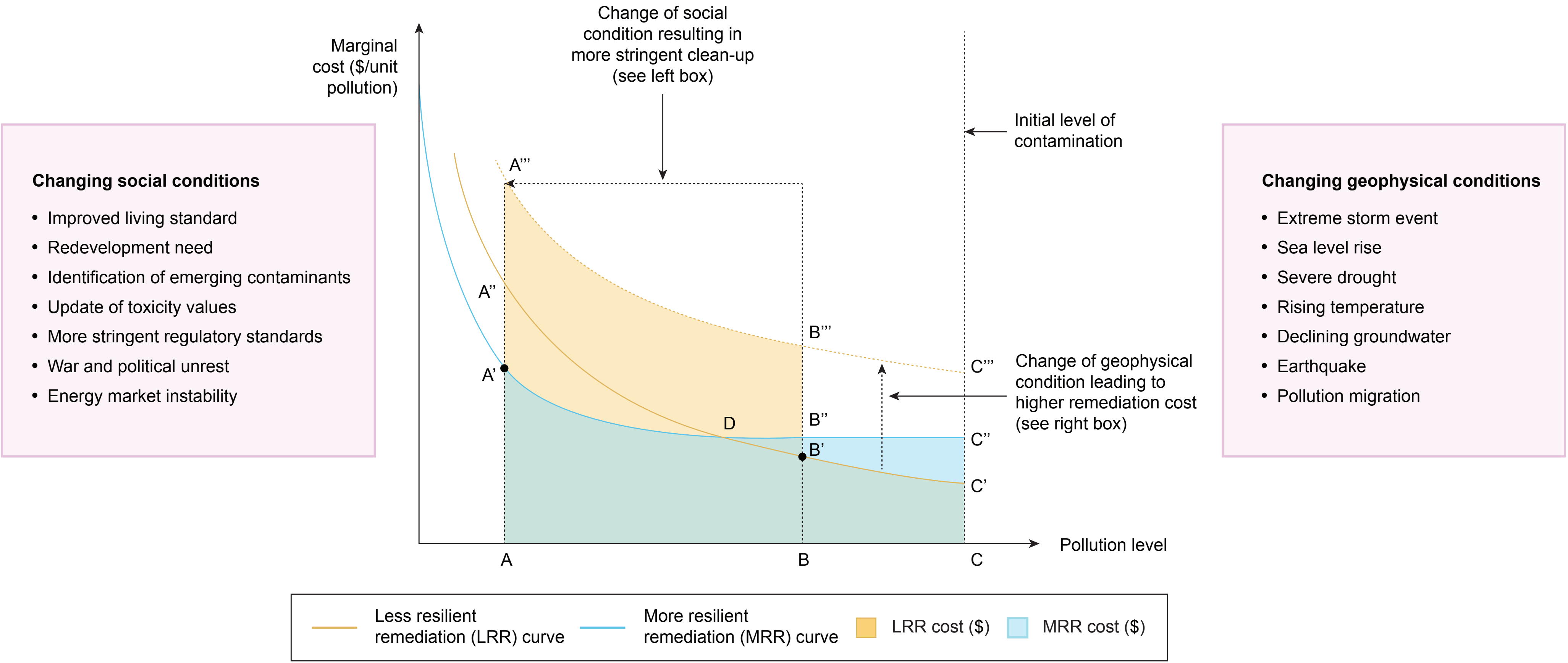

Changing social conditions
Improved living standard
Redevelopment need
Identification of emerging contaminants
Update of toxicity values
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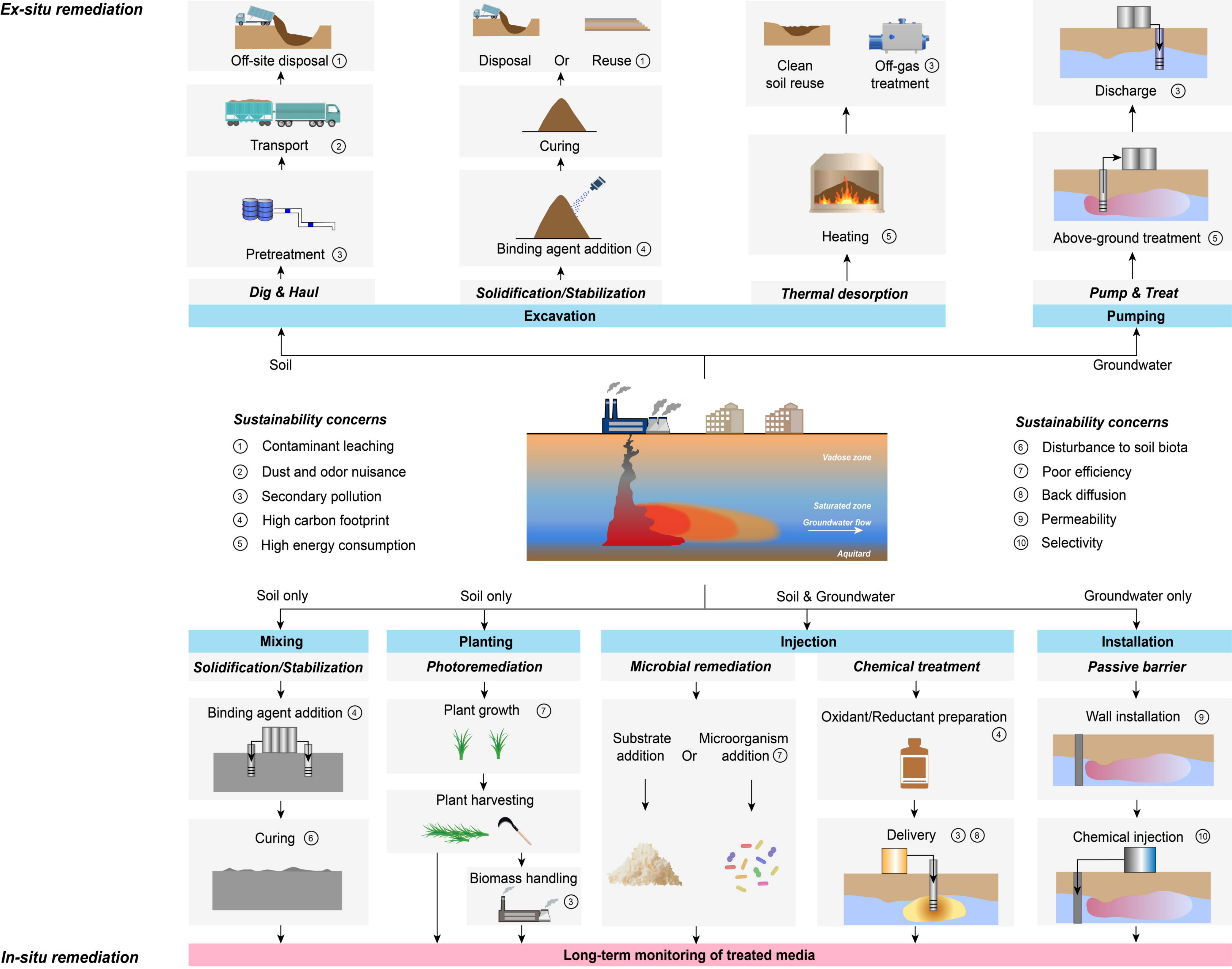
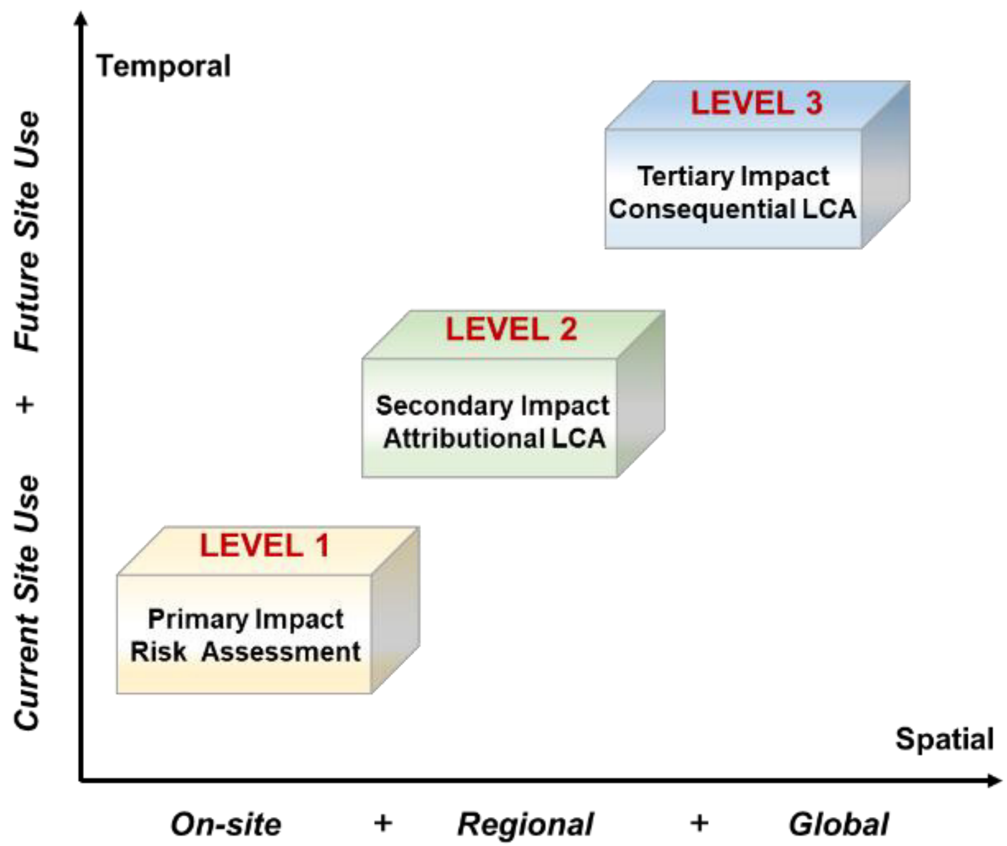
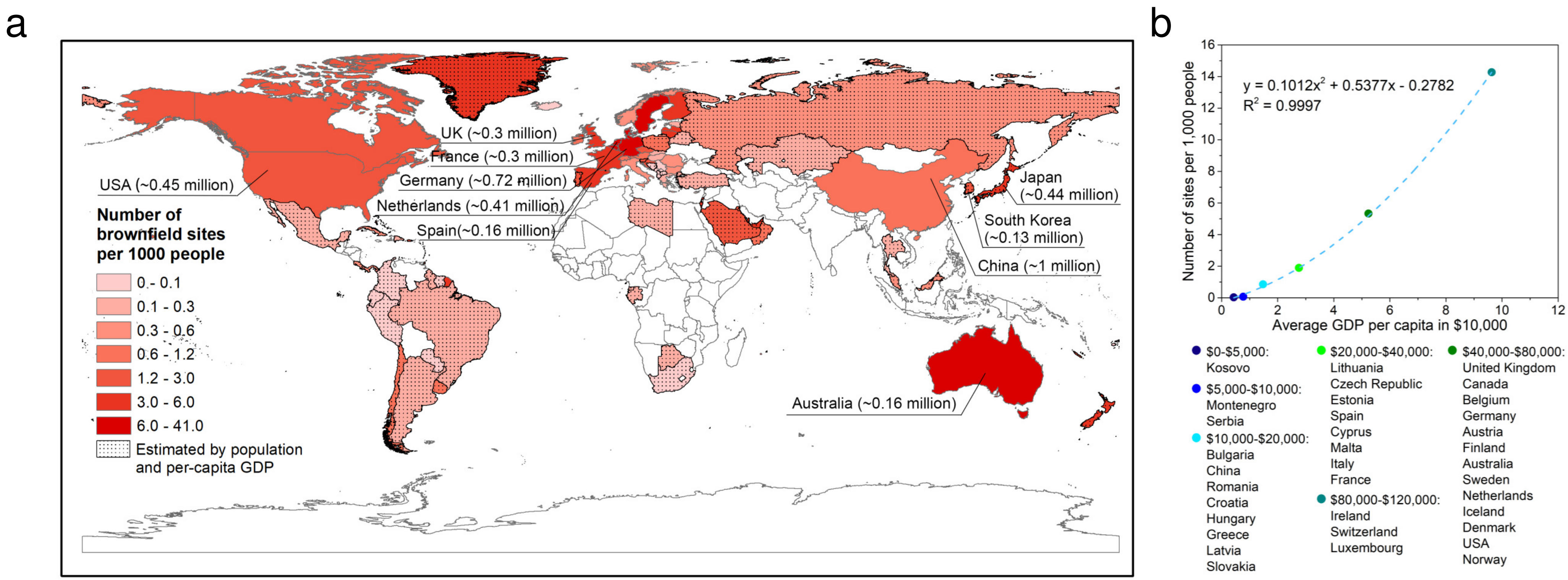
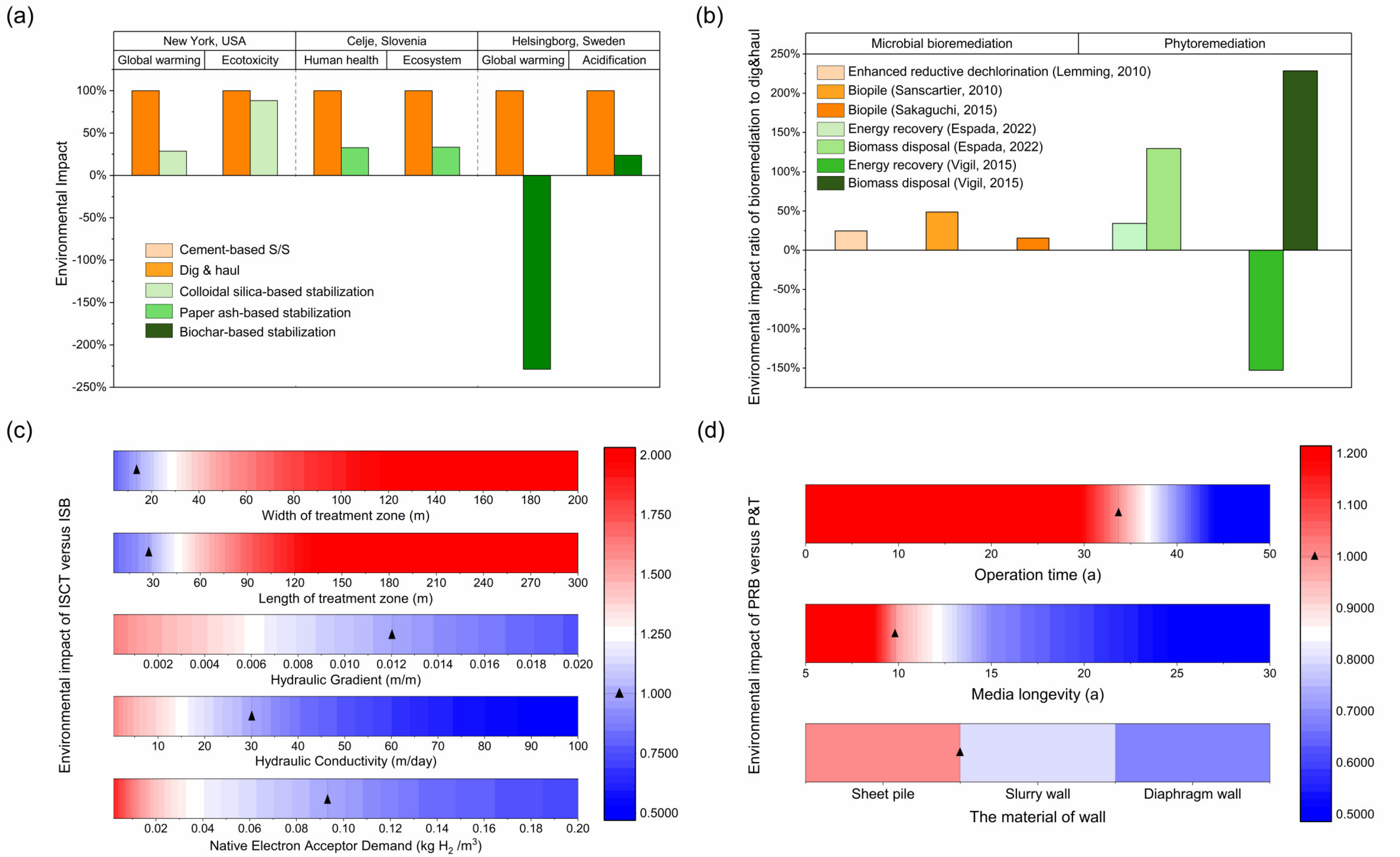
Marginal cost ($/unit pollution)
Change of social condition resulting in more stringent clean-up (see left box)
Initial level of contamination
A'''
A''
A'
D
B'''
B''
B'
C'''
C''
C'
Change of geophysical condition leading to higher remediation cost (see right box)
Pollution level
A
B
C
Changing geophysical conditions
Extreme storm event
Sea level rise
Severe drought
Rising temperature
Declining groundwater
Earthquake
Pollution migration
Less resilient remediation (LRR) curve
More resilient remediation (MRR) curve
LRR cost ($)
MRR cost ($)



Ex-situ remediation
Off-site disposal ①
Transport ②
Pretreatment ③
Dig & Haul
Disposal Or Reuse ①
Curing
Binding agent addition ④
Solidification/Stabilization
Clean soil reuse
Off-gas treatment ③
Heating ⑤
Thermal desorption
Discharge ③
Above-ground treatment ⑤
Pump & Treat
Excavation
Pumping
Soil
Groundwater
Sustainability concerns
① Contaminant leaching
② Dust and odor nuisance
③ Secondary pollution
④ High carbon footprint
⑤ High energy consumption
Vadose zone
Saturated zone
Groundwater flow
Aquitard
Sustainability concerns
⑥ Disturbance to soil biota
⑦ Poor efficiency
⑧ Back diffusion
⑨ Permeability
⑩ Selectivity
Soil only
Soil only
Soil & Groundwater
Groundwater only
Mixing
Planting
Injection
Installation
Solidification/Stabilization
Photoremediation
Microbial remediation
Chemical treatment
Passive barrier
Binding agent addition ④
Curing ⑥
Plant growth ⑦
Plant harvesting
Biomass handling ③
Substrate addition Or Microorganism addition ⑦
Oxidant/Reductant preparation ④
Delivery ③ ⑧
Wall installation ⑨
Chemical injection ⑩
Long-term monitoring of treated media
In-situ remediation


Temporal
Future Site Use
+
Current Site Use
LEVEL 3
Tertiary Impact
Consequential LCA
LEVEL 2
Secondary Impact
Attributional LCA
LEVEL 1
Primary Impact
Risk Assessment
Spatial
On-site
+
Regional
+
Global


a
UK (~0.3 million)
France (~0.3 million)
Germany (~0.72 million)
Netherlands (~0.41 million)
Spain(~0.16 million)
USA (~0.45 million)
Japan (~0.44 million)
South Korea (~0.13 million)
China (~1 million)
Australia (~0.16 million)
Number of brownfield sites per 1000 people
0.- 0.1
0.1 - 0.3
0.3 - 0.6
0.6 - 1.2
1.2 - 3.0
3.0 - 6.0
6.0 - 41.0
Estimated by population and per-capita GDP
b
y = 0.1012x2 + 0.5377x - 0.2782
R2 = 0.9997
Number of sites per 1,000 people
Average GDP per capita in $10,000
$0-$5,000: Kosovo
$5,000-$10,000: Montenegro Serbia
$10,000-$20,000: Bulgaria China Romania Croatia Hungary Greece Latvia Slovakia
$20,000-$40,000: Lithuania Czech Republic Estonia Spain Cyprus Malta Italy France
$80,000-$120,000: Ireland Switzerland Luxembourg
$40,000-$80,000: United Kingdom Canada Belgium Germany Austria Finland Australia Sweden Netherlands Iceland Denmark USA Norway


(a)
New York, USA
Celje, Slovenia
Helsingborg, Sweden
Global warming
Ecotoxicity
Human health
Ecosystem
Global warming
Acidification
Environmental Impact
Cement-based S/S
Dig & haul
Colloidal silica-based stabilization
Paper ash-based stabilization
Biochar-based stabilization
(b)
Microbial bioremediation
Phytoremediation
Environmental impact ratio of bioremediation to dig&haul
Enhanced reductive dechlorination (Lemming, 2010)
Biopile (Sanscartier, 2010)
Biopile (Sakaguchi, 2015)
Energy recovery (Espada, 2022)
Biomass disposal (Espada, 2022)
Energy recovery (Vigil, 2015)
Biomass disposal (Vigil, 2015)
(c)
Environmental impact of ISCT versus ISB
Width of treatment zone (m)
Length of treatment zone (m)
Hydraulic Gradient (m/m)
Hydraulic Conductivity (m/day)
Native Electron Acceptor Demand (kg H_2 /m^3)
(d)
Environmental impact of PRB versus P&T
Operation time (a)
Media longevity (a)
Sheet pile
Slurry wall
Diaphragm wall
The material of wall