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Comparative life-cycle sustainability assessment of centralized and decentralized remediation strategies at the city level

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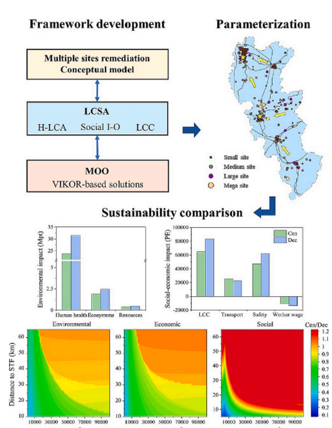
HIGHLIGHTS

- Multi-objective optimization was integrated with lifecycle sustainability assessment.
- Centralized remediation reduced environmental impacts by 25%–41% and life-cycle costs by 23%–39%.
- Soil washing was preferred for centralized remediation.
- Increased transport impact was a trade-off factor in the choice between centralized and decentralized remediation.

GRAPHICAL ABSTRACT



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ABSTRACT

Remediation of contaminated soil at industrial sites has become a challenge and an opportunity for sustainable urban land use, considering the substantial secondary impacts resulting from remediation activities. The design of soil remediation strategies for multi-site remediation from a regional perspective is of great significance for cities with a large number of brownfields. Centralized and decentralized facilities have been studied in different environmental fields, yet limited research has focused on centralized soil remediation, specifically the treatment of contaminated soil from different sites through the construction of shared soil treatment facilities. This study

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proposes a framework for comparing centralized and decentralized strategies for contaminated soil remediation based on the integration of life-cycle sustainability assessment and multi-objective optimization. With Zhuzhou, an industrial city in China, serving as an example, results show that after optimization, the centralized scenario can reduce total environmental impacts by 25 %–41 %. In addition, the centralized scenario can reduce economic costs by 27 %–39 %, saving up to 176 million USD. The advantages of the centralized soil remediation strategy include: (1) increased use of soil washing, (2) reduced use of off-site disposal, and (3) reduced construction and efficient utilization of soil treatment facilities. In conclusion, the centralized strategy is relatively suitable for cities or areas with a large number of medium or small-sized contaminated sites. The built framework can quantitatively evaluate multiple sites soil remediation at both the city and individual site level, allowing for a straightforward and objective comparison with the optimal remediation design.

1. Introduction

Soil contamination poses a great threat to the environment, human health and urban development, and soil quality is intertwined with the United Nations' Sustainable Development Goals (Bouma and Montanarella, 2016; Hou et al., 2020). In China, 16.1 % of soil samples collected in a national survey of soil quality failed to meet national soil quality standards (MEP, 2014), with industrial activities being a major cause of soil contamination. Such activities lead to brownfields, tracts of abandoned land that was developed for industrial purposes (Merriam-Webster, 2021) and are now the legacy of past urbanization and industrialization. The United States is estimated to have 450,000 brownfield sites (USEPA, 2021), and in China, 29.4 %–36.3 % of brownfield sampling sites exceed national soil quality standards, which translates to tens of millions of hectares of contaminated land (MEP, 2014; Song et al., 2019). Without proper management, brownfields are likely to remain vacant and derelict, causing land resources to be wasted, as well as threatening human health and ecology (Donaldson and Lord, 2018; Song et al., 2019; USEPA, 2021).

Brownfield redevelopment is an important measure that can improve the living environment and promote economic development through revitalization of urban areas (Ameller et al., 2020). Soil remediation is usually imperative for brownfield redevelopment to manage site contamination (Song et al., 2019). There are an estimated 5 million contaminated sites around the world (Hou et al., 2023). In many cases, the remediation design is primarily based on the conditions of a single contaminated site that presents risks to human health or the ecology, and necessitates compliance with local soil quality standards for site redevelopment. However, given that contaminated sites are frequently clustered (Van Hook, 2000), a centralized soil treatment strategy, also called a "cluster approach" (AIRE, 2013; CL:AIRE, 2012), may enable reducing costs and improving remediation efficiency by sharing fixed treatment facilities for sites located in close proximity (CL:AIRE, 2013; Hou et al., 2015a). Although there have been centralized remediation practices worldwide, little attention has been paid to the study of the environmental and socio-economic benefits of centralized remediation.

The use of a centralized municipal facility, such as a wastewater treatment plant, is not a novel idea and has been used in many fields at a regional level. Further, many studies have compared and investigated the pros and cons of centralized/decentralized facilities for water supply and treatment (Kavvada et al., 2016; Roefs et al., 2017; Shehabi et al., 2012; Vaananen and Gavrielides, 1989), solid waste treatment (Bastin and Longden, 2009; Righi et al., 2013), and energy systems (Iglesias et al., 2012; Kursun et al., 2015), with most of these studies focusing on the city or state level. Hybrid municipal systems, which are based on integrating centralized and decentralized municipal systems, have also been studied in previous research (Gleick, 2003; Liu et al., 2020). In general, centralized facilities can have lower costs than decentralized ones and are more suitable in large and densely populated areas (Iglesias et al., 2012). Many studies have focused on the optimization of centralized or hybrid facility systems (Anwar et al., 2018; Eggimann et al., 2016; Kuznetsova et al., 2019; Zhang et al., 2023), with the goal of maximizing the advantages of centralized or hybrid facility systems. Table S1 in Supplementary materials summarizes the aims and methods of previous studies, which have primarily centered on assessing the environmental performance of centralized facilities.

Life-cycle assessment (LCA) is a well-established methodology for comprehensively evaluating the environmental impacts of products or activities (ISO, 2006). LCA has been widely used to assess various topics, including chemical reagents (Samani and van der Meer, 2020), food products (Roy et al., 2009), energy supply (Abdelkareem et al., 2021), wastewater treatment (Corominas et al., 2020), and soil remediation (Hou et al., 2016; Huysegoms et al., 2018; Lemming et al., 2010). As sustainability has become a key element in city development, sustainability assessments aimed at balancing the environmental, social, and economic impacts of projects have gained popularity. Multiple-criteria decision analysis (MCDA) is one of the most widely used methods for conducting a sustainability assessment of various research subjects, including contaminated site remediation (Talukder and Hipel, 2021; Visentin et al., 2020). An MCDA enables simultaneously incorporating diverse indicators from various sustainability dimensions into an assessment, using a transparent and structured process. Life-cycle sustainability assessment (LCSA), a methodology derived from LCA, not only includes environmental footprints but also considers socio-economic performance (Sala et al., 2013). As such, a significant and growing trend is the replacement of traditional LCAs with LCSAs (Guinée et al., 2011).

To the best of our knowledge, there is no comprehensive framework integrating sustainability into a multi-site remediation project by assessing centralized/decentralized soil remediation strategies (CEN and DEC, respectively) to optimize the remediation design and maximize its overall benefit. Soil is a uniquely precious natural resource, and the reuse of treated soil has the potential for huge environmental and social-economic benefits (Hou et al., 2015b). Given the significance of dealing with soil contamination, especially in the context of sustainable brownfield site remediation and redevelopment, a comprehensive comparison between CEN based on a soil treatment facility (STF) and DEC (ex-situ remediation or off-site disposal via landfill and incineration) is necessary and can support decision making for multi-site remediation. This study aims to (1) build a comprehensive framework integrating sustainability into a multi-site remediation design, (2) compare the environmental and socio-economic impact of CEN and DEC with multi-objective optimization (MOO), and (3) identify key factors influencing sustainability. The constructed framework was applied to Zhuzhou City, China, as a case study to develop recommendations on and identify implications of soil remediation management in a city or region with a large number of brownfields.

2. Methods

2.1. The framework of remediation design and sustainability assessment

Fig. 1 shows the constructed sustainability assessment framework of CEN and DEC. In practice, remediation designs may vary based on site conditions. In addition, it is difficult to consider every single site within a region. Thus, a generalized model was first established by identifying the common characteristics of the contaminated sites through a case study and then setting up CEN (with STFs) and DEC (without STFs) scenarios. To assist the remediation design, key parameters such as site location, the volume of contaminated soil at each site, and characteristics of the contaminants were determined based on the results of existing investigations in the target region. After the design of CEN/DEC scenarios, LCSA was performed to understand the environmental, social and economic impact of them under the given assumptions. To select the ideal remediation route for each site and to maximize the remediation benefits with or without STFs, MOO was carried out. Last, sensitivity analysis was applied to provide more insight into the results and support decision-making under different situations.

2.2. Multi-site cluster remediation model

2.2.1. Brownfield site identification and contamination characterization

Zhuzhou City was analyzed as a case study to parameterize the CEN/DEC model. Zhuzhou is one of the oldest industrial cities in Hunan Province, south-central region of China. It has a total area of 11,200 km^2 and a total population of 4.08 million. In the past several decades, industrial prosperity has brought huge economic development to Zhuzhou, but it has also left a large number of brownfields. Gradually, an ecological and livable civic environment has become an essential pursuit of the local people. Owing to the lack of attention to soil protection in the past (Li et al., 2019), soil remediation and brownfield redevelopment have become imperative, but great challenges need to be overcome to achieve these goals. With the ambitious urban redevelopment plan, the scale of remediation work is found to be substantial, necessitating efforts to improve remediation efficiency while simultaneously mitigating the financial burden and minimizing environmental and social risks associated with the remediation process.

In the current study, 286 contaminated sites, mainly involving steel smelting and the chemical industry, were identified in Zhuzhou City. Since not all the sites have been fully investigated, assumptions were adopted based on existing site investigation results. Specifically, we assumed that 65 % of the soil was contaminated by heavy metals and the rest 35 % of the soil by heavy metals as well as organic compounds, mainly polycyclic aromatic hydrocarbons (PAHs). The volume of contaminated soil for each site was estimated based on the site area, average contamination rate, and contamination depth. Fig. 2(a) displays the size distribution of contaminated sites, which were classified as mega, large, medium, and small based on the volume of contaminated soil. Among the 286 sites, 85 % were small and medium sites, with average contaminated soil volumes of 4351 m^3 and 18,254 m^3, respectively. Although the large and mega sites were relatively few in number, the amount of contaminated soil from these sites accounted for 64 % of the total. The bulk density of soil was set to be 1.5 g/cm^3.

2.2.2. Remediation routes design

We assumed that the contaminated sites had variable amounts of contaminated soil depending on site scale but the same pollution characteristics. Only ex-situ remediation technologies were considered, because in-situ remediation would exhibit no differences between the CEN and DEC scenarios. As shown in Table 1, contaminated soil was classified into four categories through an analysis of the target contaminants, regional soil texture, and potentially applicable remediation technologies. Type A soil was contaminated with heavy metals and could be remediated by soil washing (SW), a technology that removes the contaminants from the soil via physical separation or chemical extraction. Hydrodynamic classification, a physical separation SW technology was assumed to be applied because it has been widely used and studied in field-scale (Kim et al., 2013; Mann, 1999; Song et al., 2018). The application of SW was considered first because it is cost-effective when a large volume of contaminated soil needs to be treated (Dermont et al., 2008). Since hydrodynamic classification may not be applicable for soil that contains a high proportion of silt or clay (Dermont et al., 2008; Sharma and Reddy, 2004), the SW application rate was assumed to be limited up to 35 % of all contaminated soil. Type B soil was contaminated with heavy metals but could not be remediated by SW due to high proportion of silt or clay. Solidification/stabilization (S/S), a common remediation technology, was adopted for type B soil. Type C soil was co-contaminated with heavy metals and PAHs. Ex-situ Chemical oxidation (ESCO), a widely used and relatively low-cost technology for treating soil polluted by organic compounds, is undertaken before S/S treatment to eliminate PAHs first. For soils co-contaminated with heavy metals and PAHs and not suitable for ESCO-S/S (type D), such as soil with very high organic matter or concentrations of PAHs, thermal desorption (TD) was used for a more complete elimination of organic contaminants; TD has a high removal efficiency for organic contaminants in general (Kuppusamy et al., 2017). In addition, off-site disposal technologies, including landfill and incineration (processed in rotary kiln-based incinerator) that can be used to treat any type of contaminated soil, were also considered because they are easy to operate and widely used in China (Liang et al., 2023; Song et al., 2018).

2.2.3. Centralized/decentralized remediation scenarios

According to the United Kingdom's Sustainable Remediation Forum (SuRF-UK) (CL:AIRE, 2012), CEN can be defined as constructing an STF

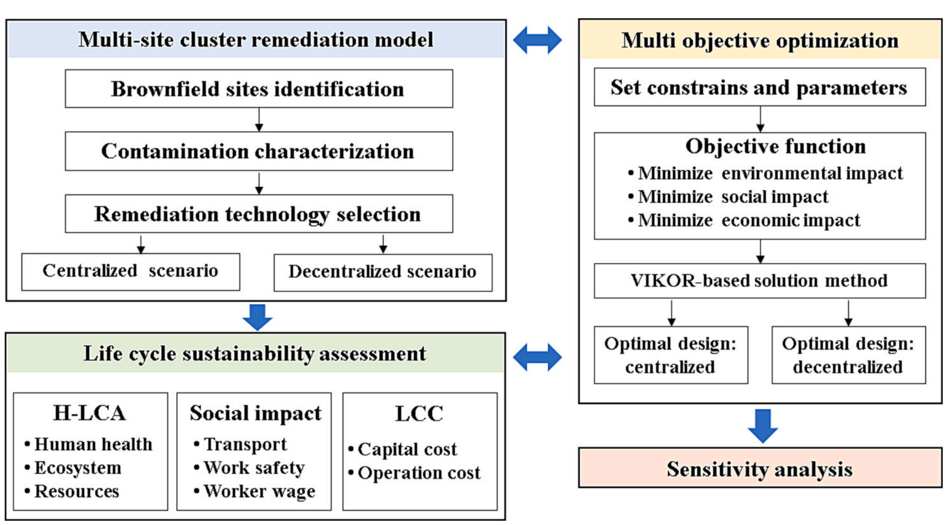

Fig. 1. The constructed sustainability assessment framework of centralized/decentralized remediation strategies (H-LCA: Hybrid lifecycle assessment, LCC: Lifecycle costing, VIKOR: Multicriteria Optimization and Compromise Solution).

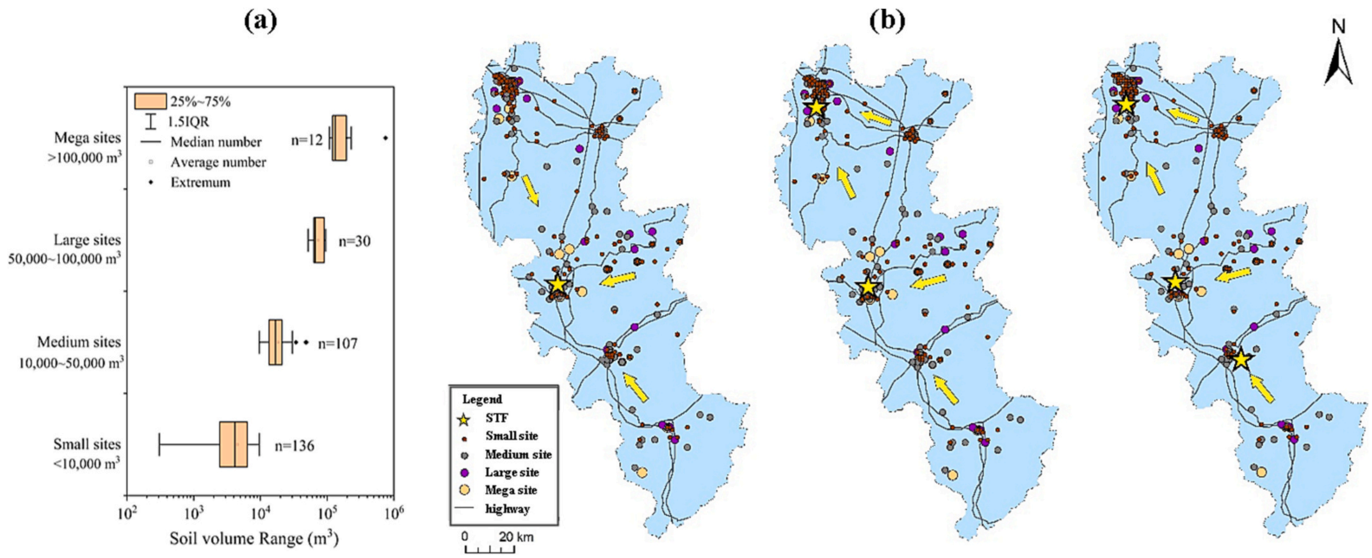

Fig. 2. Size distribution (a) and locations (b) of contaminated sites in the studied area with 1, 2, and 3 STFs suggested for establishment (the yellow arrows indicate the direction for soil flow).

Table 1
Overview of alternative remediation technologies for each soil type in either centralized (CEN) or decentralized (DEN) remediation scenario.

Soil type	Alternative remediation technologies									Assumed total utilization rate
	SW		S/S		ESCO-S/S		TD-S/S		Landfill/incineration	
	CEN	DEC	CEN	DEC	CEN	DEC	CEN	DEC	CEN/DEC	
A	1/2	2	1/2	2	N/A	N/A	N/A	N/A	2	0.35
B	N/A	N/A	1/2	2	N/A	N/A	N/A	N/A	2	0.3
C	N/A	N/A	N/A	N/A	1/2	2	N/A	N/A	2	0.2
D	N/A	N/A	N/A	N/A	N/A	N/A	1/2	2	2	0.15

Note: 1 = off-site remediation: soil excavated and transport to the nearby STF or disposal facility; 2 = ex-situ remediation: on-site installation and operation of remediation system for the treatment of excavated soil; N/A = not applicable; SW = soil washing; S/S = stabilization/solidification; ESCO-S/S = stabilization/solidification after ex-situ chemical oxidation, TD-S/S = stabilization/solidification after thermal desorption.

at a "hub site" for off-site remediation of contaminated soil from other "donor sites". In the CEN scenario, STF numbers and locations were determined as follows: (1) Several potential STF locations were identified to be located in large or mega contaminated sites where the kernel density of brownfields is high; (2) It is assumed that there could be 1–3 STFs based on the real-world consideration, and contaminated sites are evenly distributed to different STFs to balance the treatment volume; (3) Then, the final STF locations are determined based on the given STF number and minimization of transportation and construction costs. Fig. 2(b) shows three possible scenarios of CEN with different STF numbers. Fig. 3(a) is the illustration of CEN. The construction of 2 STFs is selected as the baseline CEN scenario, and the others are studied in

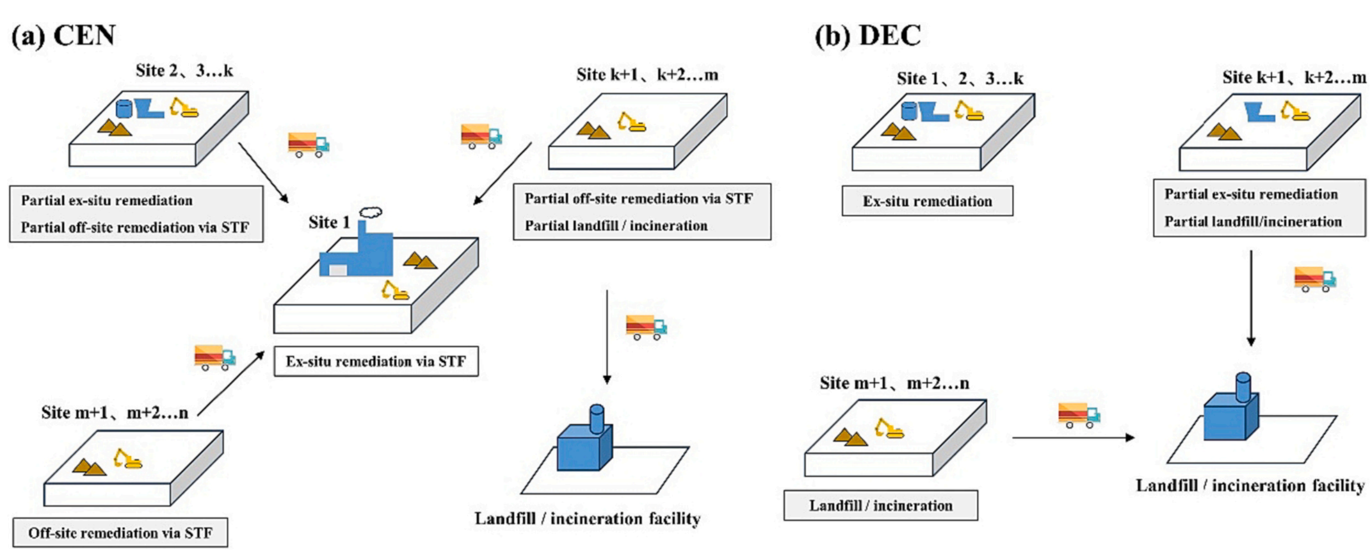

Fig. 3. Illustration of centralized remediation scenario (a) and decentralized remediation scenario (b).

sensitivity analysis. In addition, ex-situ remediation and off-site disposal are also available in the CEN scenario.

In contrast to CEN, which involves the construction of fixed remediation facilities receiving contaminated soil from multiple sites, DEC is carried out individually for each site. DEC involves ex-situ remediation through the utilization of rented mobile remediation equipment and off-site disposal through landfill or incineration. Table S2 in Supplementary materials shows the detailed descriptions of ex-situ remediation and STF design. The selection of remediation technologies and the remediation strategies (ex-situ or off-site remediation) is based on the soil type (see Table 1).

2.3. Lifecycle sustainability assessment methodology

2.3.1. Goal and scope

The goal of LCSA is to explore the environmental and socio-economic performance of CEN and DEN soil remediation strategies through an LCA-based approach. The functional unit should be the same for the scenarios being compared. In this study, that unit was treatment of the total volumes of 7.15 million m^3 contaminated soil from the targeted sites in Zhuzhou City. The lifecycle impact of remediation can be divided into three categories (Morais and Delerue-Matos, 2010; Owsianiak et al., 2013): (a) primary impact associated with the contaminants fate and exposure; (b) secondary impact associated with the remediation activities; (c) tertiary impact associated with the consequential results due to the use of site after remediation. This study only consider the secondary impact since the other two are assumed to be the same.

The system boundary included all remediation-related activities in three phases: (a) contaminated soil excavation and transportation, (b) construction of STFs for off-site remediation and on-site facilities for ex-situ remediation, and (c) remediation operation and management. In phase (a), the transport of soil after remediation was excluded because it was assumed that the reuse process has a minimal impact and is in charge of the city planning authorities. In phase (b), construction activities refer to the construction and installation of remediation equipment and ancillary facilities, such as the temporary pavement, remediation shed, and secondary pollution control system. It is supposed that mobile soil remediation facilities are used for ex-situ remediation in both CEN and DEC scenarios. In phase (c), post-remediation management activities including backfill with low-permeability layer, monitoring well construction and long-term monitoring were needed for the S/S-treated soil, because the heavy metals still remain and the long-term effectiveness of S/S needs to be verified according to the regulation requirement (Correia et al., 2020; Shen et al., 2019).

2.3.2. Hybrid lifecycle assessment

For the environmental impact assessment, a hybrid LCA (H-LCA), which combines the process-based LCA with an economic input-output (EIO) model, can take advantage of the accuracy of the process analysis as well as the simplicity and completeness of an EIO analysis (Lenzen and Crawford, 2009). This study used a previously described H-LCA approach (Suh et al., 2004) to quantify the overall environmental impact of CEN and DEC for multiple sites.

As great uncertainty exists regarding the inventory data of STF and on-site construction activities (phase b activities) needed by a process-based LCA, an EIO-LCA based on the 2017 Chinese Environmentally Extended Input-Output (CEEIO) database was applied. CEEIO was developed by Liang et al. (Liang et al., 2017) and Tian et al. (Tian et al., 2021) and consists of 49 industrial sectors. Through analyzing a detailed cost breakdown of a remediation project already done in Zhuzhou City,

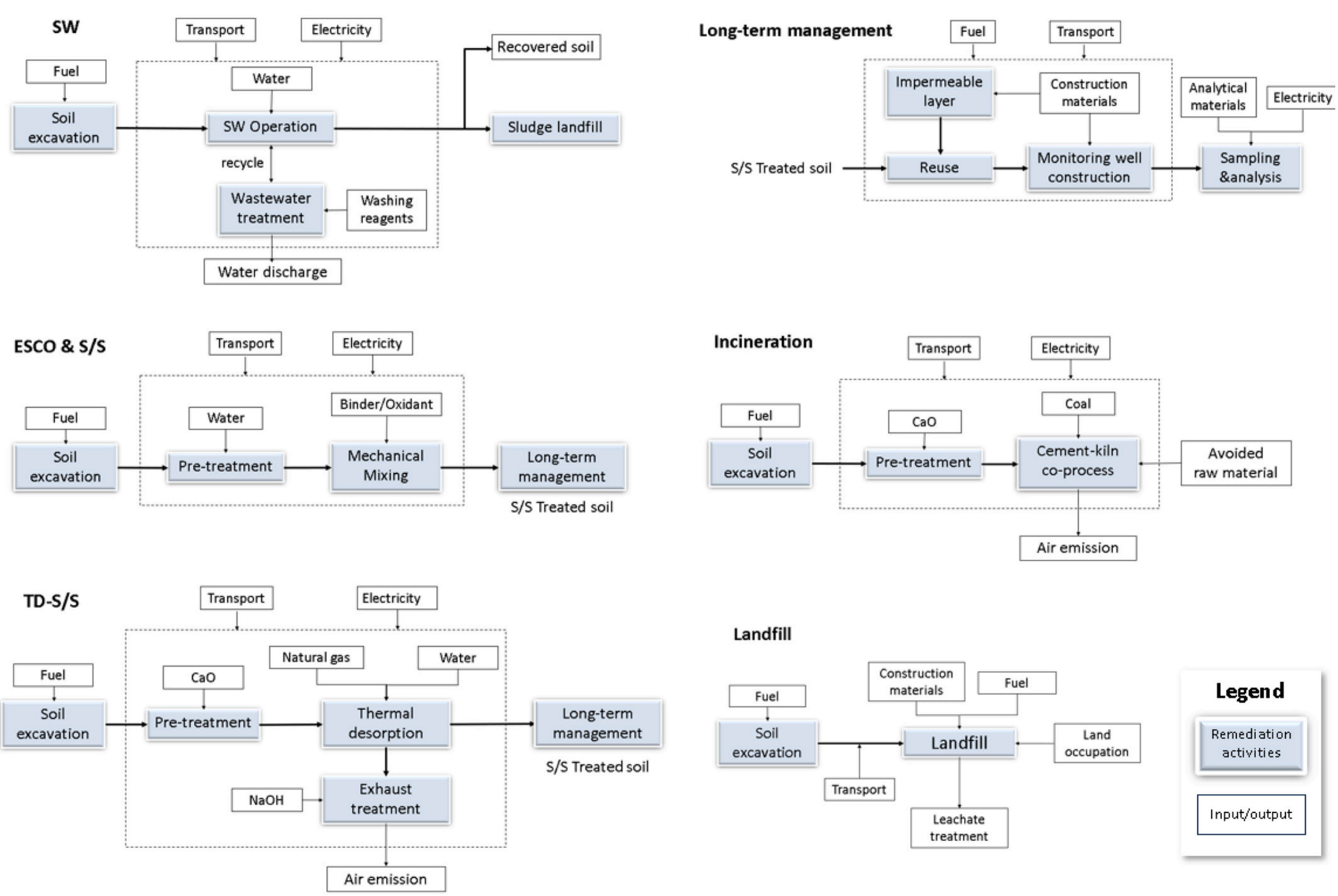

Fig. 4. System boundaries of remediation technologies.

an economic input allocation for each industry sector was determined. The economic input for remediation construction is shown in Table S3 in Supplementary materials.

As shown in Fig. 4, the system boundary of a process-based LCA included the materials and energy acquisition, transportation, and emissions from processes other than construction for the remediation technologies used in CEN and DEC scenarios. These processes were mainly related to excavation, remediation operations, and waste management. The life-cycle inventory was derived from remediation project documents as well as literature review. The main differences between the inventory of DEC and CEN are the utilization rates of ex-situ and off-site remediation technologies, the cost of construction activities, and the amount of contaminated soil transported. The detailed information on life-cycle inventory is shown in Tables S4, S5 and S6 in Supplementary materials.

The life-cycle impact assessment was performed using software SimaPro 9.1 with the ReCiPe 2016 model (Huijbregts et al., 2017), a lifecycle impact assessment method widely used to evaluate the environmental impact of remediation (Huysegoms et al., 2018; Jin et al., 2021; Song et al., 2018). The ReCiPe model has 22 midpoint indicators to comprehensively describe the environmental impact and three endpoint indicators (human health, ecosystems, and resources), and it further integrates these impacts to derive a single score to assist decision-making, albeit with higher uncertainty (Hauschild, 2005). This study used the default endpoint indicators, hierarchist version, which allowed for straightforward interpretation of the results. Also, given the importance of greenhouse gas mitigation under the goal of carbon neutralization in China (Wang et al., 2021), the carbon footprint was analyzed independently by using IPCC 2013 GWP 20a method (Stocker, 2014), embedded in SimaPro.

2.3.3. Social impact assessment

The social impact indicators considered in this study included work fatalities, worker wage, and the impact of transportation. Safety is the highest priority social indicator in most cases (Cappuyns, 2016), with work fatalities selected as the output parameter. Worker wage is regarded within both the social and economic domains, as it somehow reflects employment opportunities (Braun et al., 2021; Hou et al., 2014; Reddy et al., 2014) and direct economic benefits (Bardos et al., 2009). While worker wages are not commonly addressed in the sustainability assessment of remediation(Cappuyns, 2016; Huysegoms and Cappuyns, 2017), they remain a matter of significant social concern in developing countries(Initiative, 2009). The impact of transportation closely relates to environmental disturbance of the local community caused by remediation (e.g., air quality, contaminants exposure risk, and noise), traffic congestion, and "wear and tear" of roads (Petruzzi, 2011), particularly when ex-situ remediation is carried out. The selection of these social indicators was premised on quantification with existing data reflecting different aspects of social sustainability.

Work fatalities and worker wage were quantified by an input-output model based on CEEIO database. The death toll from industrial production safety accidents and road traffic from the Statistical Yearbook of China and Hunan Province (Statistics, 2018a; Statistics, 2018b) were used to derive IO multipliers. The impact of transportation was measured though product of transport distance and mass load.

2.3.4. Life-cycle cost

The life-cycle cost (LCC) has the same system boundary as LCA (Ding et al., 2022; Visentin et al., 2019), considering capital costs, operation costs, and management costs. In this study, LCC was calculated using the following equation:

$$LCC = \sum_{i}\sum_{x} C_{c,x,i} + \sum_{j}\sum_{y} m_{\mathrm{R},y,j} \cdot U_{R,j} + \sum_{z} m_{\mathrm{Tr},z} \cdot D_z \cdot U_{\mathrm{Tr}} \tag{1}$$

where $C_{C,x,i}$ is the capital cost of i (on-site construction, STF construction) for site x; $m_{\mathrm{R},y,j}$ is the contaminated soil mass treated by remediation technology j for site y; $U_{\mathrm{R},j}$ is the unit cost of remediation technology j; $m_{\mathrm{Tr},z}$ is the contaminated soil mass of site z that needs to be transported off site; D_z is the transport distance; and U_{Tr} is the unit cost of soil transport.

2.4. Multi-objective optimization

2.4.1. Objective functions

Although all the contaminated soil could be sent to an STF for off-site treatment after excavation under CEN scenario, trade-offs existed between the environmental and social-economic performance of ex-situ remediation and off-site remediation. For example, part of the contaminated soil could be sent to an STF, with the remaining part undergoing ex-situ remediation or off-site disposal. Therefore, MOO is carried out to select the most sustainable remediation technology combination for each contaminated site under CEN or DEC scenarios, with the aim of minimizing the total environmental impact, social impact, and LCC. For an individual site, the objective functions can be expressed by Eqs. (2) to (4):

$$Min\ Env = \sum_{i} w_{env,i} \cdot EI_i \tag{2}$$

$$Min\ Soc = \sum_{i} w_{soc,i} \cdot \frac{SI_i}{NF_{soc,i}} \tag{3}$$

$$Min\ LCC = \frac{LCC}{NF_{LCC}} \tag{4}$$

where EI_i is the environmental impact indicators corresponding to ReCiPe endpoint indicators human health, ecosystem, and resources; SI_i is the social impact indicators corresponding to worker safety, impact of contaminated soil transport (t·km), and worker wage (CNY); w is the weighting factor, with the weights of the environmental/social indicators equal to 1; and NF is the normalization factor. The social and economic results are normalized to person equivalent (PE) to assist in interpretation. Being consistent with environmental impact assessment, the positive value of PE indicates negative impact, vice versa.

The weights of environmental indicators were determined by the ReCiPe 2016 endpoint method (Huijbregts et al., 2017). The weights of social indicators were determined by the Analytic Hierarchy Process (AHP), a subjective weighting method that considers the expertise and knowledge of experts, as well as the intentions and preferences of decision makers (Saaty, 2008). The results of NF and AHP are presented in Tables S7 and S8 in Supplementary materials, respectively.

2.4.2. Decision variables

In the remediation design for each site, selecting the appropriate technology combinations was essential. Therefore, the remediation technology utilization rate for different pollutant types were set as decision variables, as shown in Table 1. In addition, binary variables were applied to the input of construction activities.

2.4.3. Constraints

The MOO constrains were designed based on the cluster remediation conceptual model as described in Section 2.2. There were four types of constrains: site condition constraints, contamination characteristics constraints, remediation technology utilization constraints, and treatment capacity constraints.

(1) Site condition constraints: the soil transport distance is constrained by the site/STF number, site/STF locations, and contaminated soil volume of each site. The site conditions are described in Section 2.2.1.

(2) Contamination characteristics constraints: as described in Section 2.2.3, the proportion of each contamination soil type is supposed to be same for any given site.
(3) Remediation technology utilization constraints: As shown in Table 1, the sum of each remediation technology utilization rate should be equal to 1. Meanwhile, the utilization rate of technologies applicable to each type of contaminated soil should not exceed the proportion corresponding to that type of soil.
(4) Treatment capacity constraints: The treatment capacity of STFs and on-site remediation facilities should not lower than the total amount of target soil through their lifecycle. These constraints will determine the capital cost estimation of STF/on-site constructions.

2.4.4. Solution method

For a multidimensional system for which sustainability needs to be maximized, improving one objective may result in the deterioration of other objectives (Cambero and Sowlati, 2014). To find compromises and achieve a solution, a VIKOR-based method was adopted in this study. VIKOR stands for "VIseKriterijumska Optimizacija I Kompromisno Resenje" that translates from Serbian as "multi-criteria optimization and compromise solution"(Opricović, 1998). For any contaminated site, the best remediation option satisfies the following equations (Opricovic and Tzeng, 2004):

$$S_i = \sum_{j=1}^{n} w_j \cdot \frac{f_{j,max} - f_{i,j}}{f_{j,max} - f_{j,min}} \tag{5}$$

$$R_i = min_j \left(w_j \cdot \frac{f_{j,max} - f_{i,j}}{f_{j,max} - f_{j,min}} \right) \tag{6}$$

$$Q_i = v \cdot \frac{S_i - S_{min}}{S_{max} - S_{min}} + (1 - v) \frac{R_i - R_{min}}{R_{max} - R_{min}} \tag{7}$$

where S_i, R_i, and Q_i are the maximum group utility, individual regret, and sustainability score of remediation option i, respectively; w_j is the weight of sustainability impact j. $f_{i,j}$ is the impact j of remediation option i calculated by Eqs. (2)–(4); and v is the weight of the maximum group utility. In this study, v was set to 0.5 (Aydın and Kahraman, 2014; Chen et al., 2022; Zheng et al., 2019), representing the balance of overall interests and individual equality. The variations of w_j reflect different preferences in decision-making. In this study, the default weights of environmental, economic, and social sustainability were set to 0.4, 0.4, and 0.2, supposing that the environmental and economic costs are equally important, and social impact is an auxiliary criterion.

Q_i is arranged in descending order of Q_{A1}, Q_{A2} …… Q_{An}, and the optimal solution Q_{A1} should satisfied the following conditions:

$$Q_{A1} - Q_{A2} > \frac{1}{n-1} \tag{8}$$

The developed MOO model could be solved using commercially available non-linear solvers.

2.5. Interpretation

The results of the LCSA of the optimized scenarios are presented as absolute values, and the comparative results are from both regional and individual site perspectives.

The study results are partly related to the key assumptions made. Sensitivity analysis was carried out to further explore the relative sustainability of CEN or DEC under different scenarios. The following parameters were evaluated in a sensitivity analysis: average soil transportation distance from site to landfill and incineration facilities (×0.5/×2), the maximum SW utilization rate (0 %/70 %), capital cost (70 %/130 %), and the number of STFs (1/3). The relative sustainability under varying parameter input conditions were obtained by the following equation:

$$R = \frac{CEN_i}{DEC_i} \tag{9}$$

where CEN_i and DEC_i are the normalized values of environmental, social and economic impacts calculated by Eqs. (2)–(4) for centralized and decentralized remediation scenarios, respectively.

3. Results and discussion

3.1. Optimization results of CEN and DEC

Fig. 5(a) and (c) shows the soil mass flow analysis of the optimized solutions. Under the CEN scenario, more than 72 % of the contaminated soil was sent to an STF, with the remaining nearly 28 % undergoing on-site remediation. Under the DEC scenario, the proportion of on-site remediation reached 82 %, and the remainder, mainly involving soil co-contaminated with heavy metals and PAHs, was sent for off-site disposal. With the construction of STFs, the adoption rate of SW and TD-S/S increased significantly, replacing the application of S/S and off-site disposal, respectively. This result is due to SW and TD-S/S having a high capital cost (Eagle et al., 1993; Kingscott and Weisman, 2002). The marginal benefits of these methods expanded as the amount of soil being treated increased, and thus, they were more suitable for the CEN scenario or large site remediation.

Fig. 5(b) and (d) shows the contribution of the processes to the total environmental impact and cost. The environmental and economic contributions of each process were generally similar in both scenarios. The remediation operation process in the CEN/DEC scenario accounted for 88 %/92 % and 79 %/86 % of the total environmental/economic impact, respectively. Previous studies also indicated that the remediation operation could be a major process in the life-cycle environmental impacts (Lemming et al., 2010; Ni et al., 2020). Although the cost of STF construction was high, the impact contribution of construction process in DEC was three times higher than that of CEN, due to reduced application of on-site remediation. In addition, we found that SW only contributed 9 % of the environmental impact and 15 % of the economic impact with a 26 % application rate. In the DEC scenario, 18 % of the total contaminated soil was sent for off-site disposal, while they contributed 29 % and 34 % of the environmental and economic impacts, respectively.

These results indicate that SW (hydrodynamic classification) has relatively low secondary impact when treating large amounts of contaminated soil compared with alternative remediation options, which is consistent with previous studies (Amponsah et al., 2018; Hou et al., 2014; Song et al., 2018). There are successful cases of an STF using SW, such as the London Olympic Park remediation project. In that project, through SW of 700,000 m^3 of contaminated soil, 80 %–85 % of treated soil was reused, resulting in 87 % environmental impact reduction compared with the use of a landfill (Hou et al., 2015a).

3.2. Life-cycle sustainability assessment

The ReCiPe endpoint environmental impact scores of the two scenarios are shown in Fig. 6(a). CEN had better environmental performance in all three impact categories (ecosystem, human health, and resources), and the total environmental impact was 25 % lower than that of the DEC. Social and economic impacts expressed in PE are shown in Fig. 6(b). The CEN strategy cost 4064 million CNY, rendering 132 million t·km of contaminated soil transport, 0.36 work fatalities, and 575 million CNY in worker wage. The DEC strategy resulted in 28 % higher LCC and wage, 32 % more work fatalities, and 12 % lower transport impact. Safety risks were divided into three parts: (1) risks caused by construction activities, (2) risks caused by transport activities, and (3) risks caused by remediation operation. Different normalization

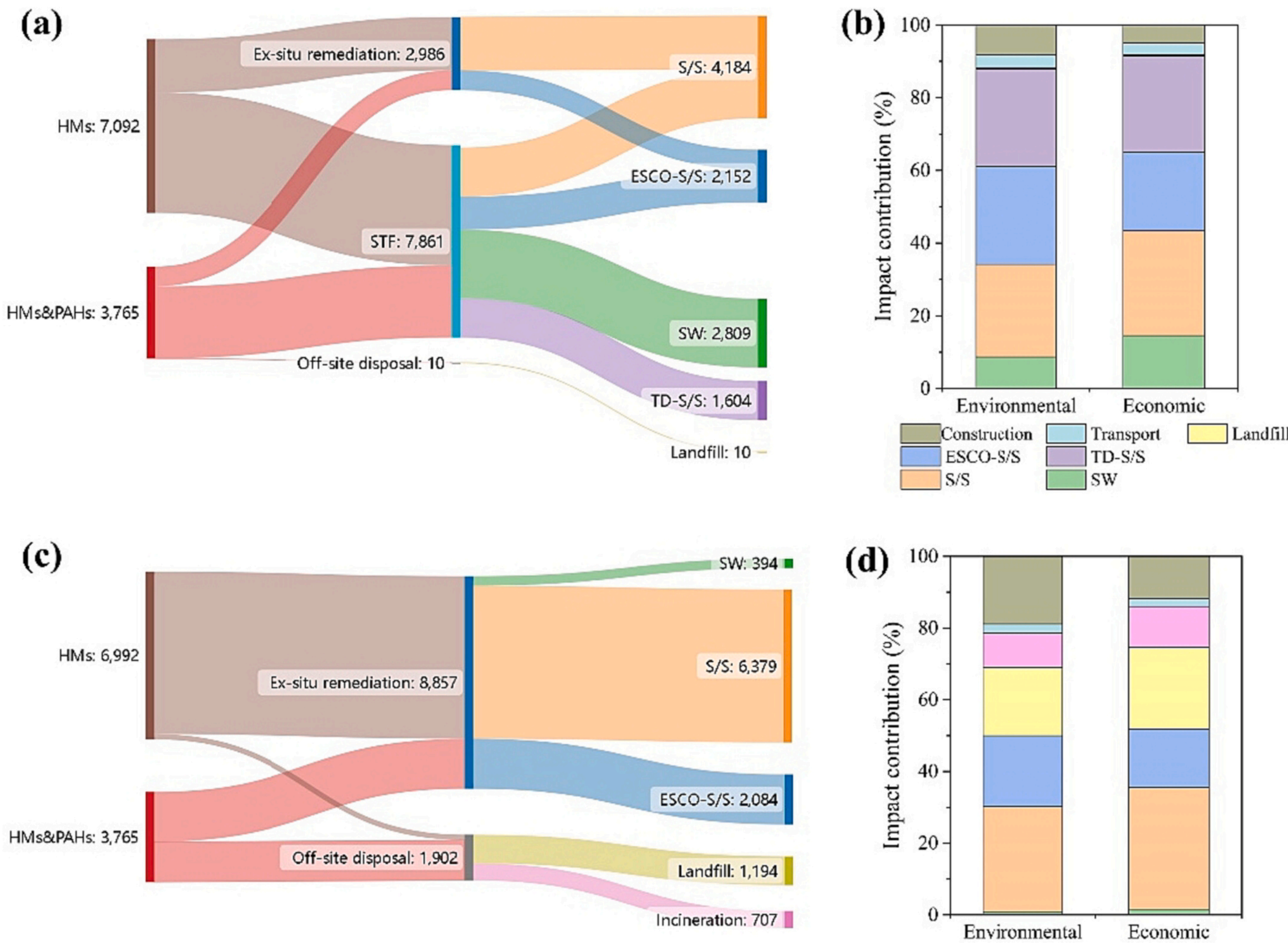

Fig. 5. Soil mass flow and process contribution analysis of optimized centralized scenario (a), (b) and decentralized scenario (c), (d). HMs = soil contaminated with heavy metals; HMs&PAHs = soil c-contaminated with heavy metals and PAHs. The mass unit is kt.

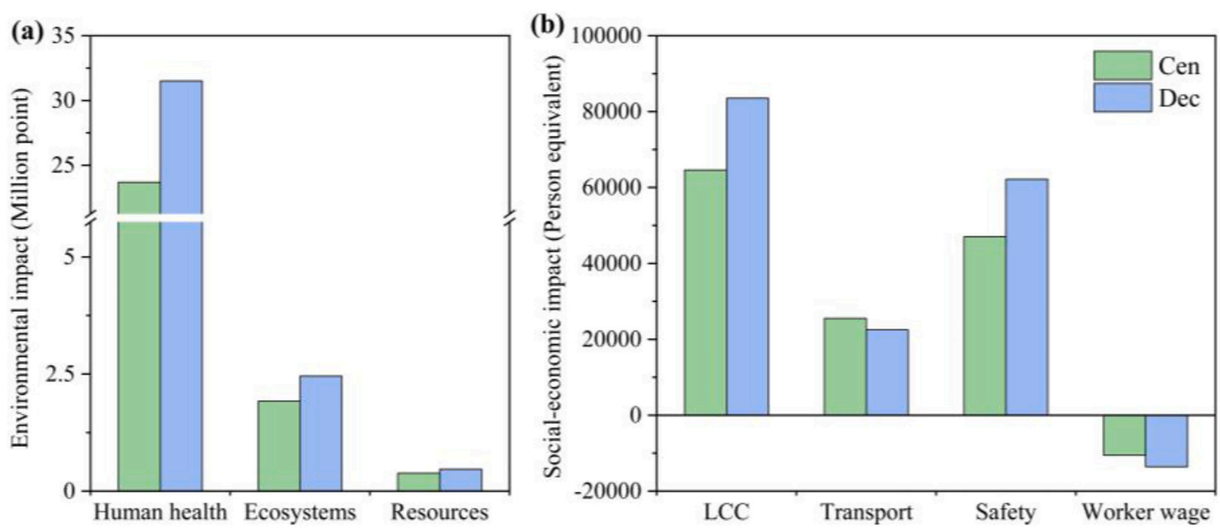

Fig. 6. Life-cycle sustainability impact comparison of centralized and decentralized remediation scenarios.

factors were applied to quantify the total safety risks (see Table S7). Overall, safety and wage increased as remediation costs rose, because this study used the I—O method for the social impact quantification. DEC had lower contaminated soil transport, because a much higher proportion of on-site remediation was being carried out. It should be noted that a large amount of contaminated soil (1901 kt) was sent for off-site disposal, which somewhat offset the advantage of reduced transport impact due to on-site remediation. Combined with the previous analysis, the environmental and social-economic benefits of CEN could be attributed to three aspects: (1) increased application rate of SW,

(2) reduced application rate of off-site disposal, and (3) reduction in construction input for and efficient utilization of STF.

3.3. Sensitivity analysis

Sensitivity analysis was performed by changing the value of several hypothetical parameters. Fig. 7(a) shows the trend in relative sustainability as a function of transport distance to off-site disposal facilities. The average transport distance of landfill and incineration facilities was set to 50 km and 80 km, respectively, to represent common scenarios. In practice, transport distance may vary greatly from site to site. For example, Liang et al. (Liang et al., 2023) reviewed 31 cases of contaminated soil incineration and found that the soil transport distances ranged from 15 to 263 km. As the transport distance to off-site disposal facilities increased, the relative sustainability of CEN decreased in all three dimensions. Social sustainability had high sensitivity to transport distance. When the average distances to a landfill and an incineration plant were halved, the off-site disposal application rate increased in both scenarios, resulting in the transport impact of CEN being twice that of DEC, while the safety risks of DEC were still higher than those of CEN (see Table S9 in Supplementary materials). High transport demand can be a potential drawback of CEN facilities under certain circumstances (Bastin and Longden, 2009; Yalcinkaya, 2020).

Among the ex-situ remediation technologies discussed in this study, SW is desirable when STFs were constructed. Given that the effectiveness of SW depends on the content of coarse particles in the excavated soil (Semer and Reddy, 1996), this study assumed that the SW utilization rate would be no more than 35 % at all sites to represent the general characteristics of contamination in the region. As Fig. 7(b) shows, the impact of the site geological conditions on the relative sustainability of CEN was investigated by varying the maximum SW utilization rate. The results show that the sustainability of CEN and DEC both improved with an increase in the maximum SW utilization rate (see Table S9 in Supplementary materials), and CEN was more sensitive to SW compared with DEC, especially in terms of environmental and economic impacts. It is worth noting that when SW was not applicable, CEN still had about a 20 % reduction in impact for all three aspects, indicating that the sustainability of CEN arises from the joint action of multiple factors.

There are inevitable uncertainties in capital cost estimation, specifically pertaining to the construction and installation expenses of on-site remediation system and STF (Tan et al., 2014; Wang and McTernan, 2002). Fig. 7(c) shows the trend in relative sustainability as a function of

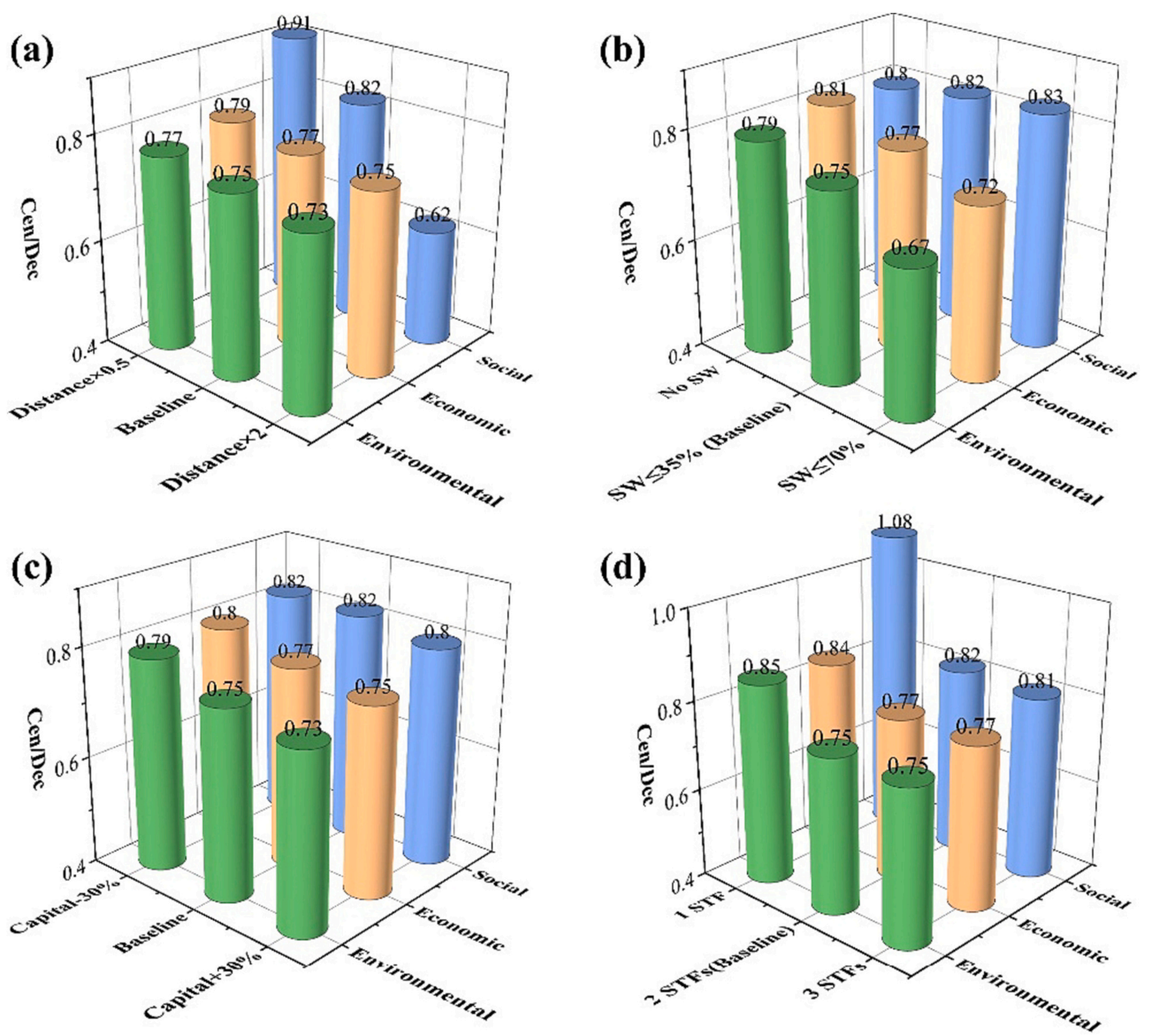

Fig. 7. Sensitivity analysis of key hypothetical parameters: (a) transport distance to disposal facilities ×0.5/1/2, (b) maximum soil washing utilization rate 0/35 %/70 %, (c) capital cost 70 %/100 %/130 %, and (d) 1/2/3 STF construction.

the capital cost. The capital cost of DEC was three times that of CEN under the baseline condition. As capital cost increased, CEN became increasingly desirable in terms of environmental and economic performance. Previous research also showed that centralized systems or clustered systems with relatively fewer constructed facilities tend to be cost-saving (Jung et al., 2018; Vaananen and Gavrielides, 1989). There was no clear trend between relative social impact and capital cost in the current study, possibly because the results of social indicators were inversely affected by capital cost.

The number and locations of STFs was obviously an important consideration in the CEN design. In this study, the STF was assumed to be constructed on one of the identified contaminated sites, and as a prerequisite for carrying out MOO. The site locations were selected based on kernel density to save transport and construction cost. The relative sustainability results of different STF numbers are shown in Fig. 7(d). When there was only one STF, the relative impact somewhat increased in all 3 domains of sustainability, especially in the social one, mainly because the transport impact increased by 40 % (see Table S9 in Supplementary materials). However, compared with the baseline scenario, the results changed slightly when one more STF were constructed. This outcome indicates that the impacts resulting from STFs construction and soil transport could be balanced.

3.4. Centralized remediation schemes based of life-cycle sustainability

CEN has been proved to have multiple advantages compared with DEC at the city level, under the assumption that cleanup occurs at all the identified sites in this case study. However, given that remediation of all contaminated sites would require huge financial, labor, and resources inputs, remediation decision-making needs to prioritize individual sites to maximize the benefit of STFs. As shown in Fig. 8(a)–(c), for individual sites, the benefits of sending contaminated soil to an STF were highly dependent on the site location and the amount of soil to be treated. CEN was more advantageous when sites with a small soil volume and at a short distance were being treated (e.g., more than 50 % impact reduction in all three dimensions). For small to large sites within a transport distance of 70 km, CEN had advantages over DEC in both environmental and economic aspects, but social impact became a dominant factor in remediation decision-making as the site size and transport distance increased. For example, if a large or mega site was at a remote location from an STF, the remediation design tended to adopt a hybrid mode; that is, part of the contaminated soil (type A) was sent to the STF, and the rest was remediated on-site.

Fig. 8(d)–(e) shows the environmental and economic benefits of CEN compared with DEC as the amount of contaminated soil increased. When the amount of contaminated soil remediation reached around 200,000 m^3, CEN began to show advantages over DEC in both environmental and economic performance. To maximize the overall benefits, advantageous sites (in the lower left area in Fig. 8(a)–(c)) could be prioritized as remediation targets of CEN. The relative benefits of CEN showed a trend of first increasing and then decreasing, with environmental impacts reduced by 25 %–41 % and life-cycle costs reduced by 23 %–39 %. CEN led to cumulative net environmental benefits of 8469 kpt ReCiPe endpoint impact reduction and economic benefits of 1190 million CNY (equivalent to 176 million USD) cost saving. Given the importance of carbon sequestration as a strategic goal at the regional level (Hou et al., 2023; Sachs, 2021), the greenhouse emissions from remediation were also evaluated. Results of IPCC 2013 GWP 20a showed that the global warming potential of CEN is 7.37×10^5 t CO_2eq, while that of DEC is 8.92×10^5 t CO_2eq; that is, CEN reduces greenhouse gas emissions by 1.55×10^5 t CO_2eq compared with DEC.

For this study, the CEN scenario included two STFs, while in some other studies the scenario with more than one center is defined as “clustered” (Anwar et al., 2018). In general, a smaller area with a higher

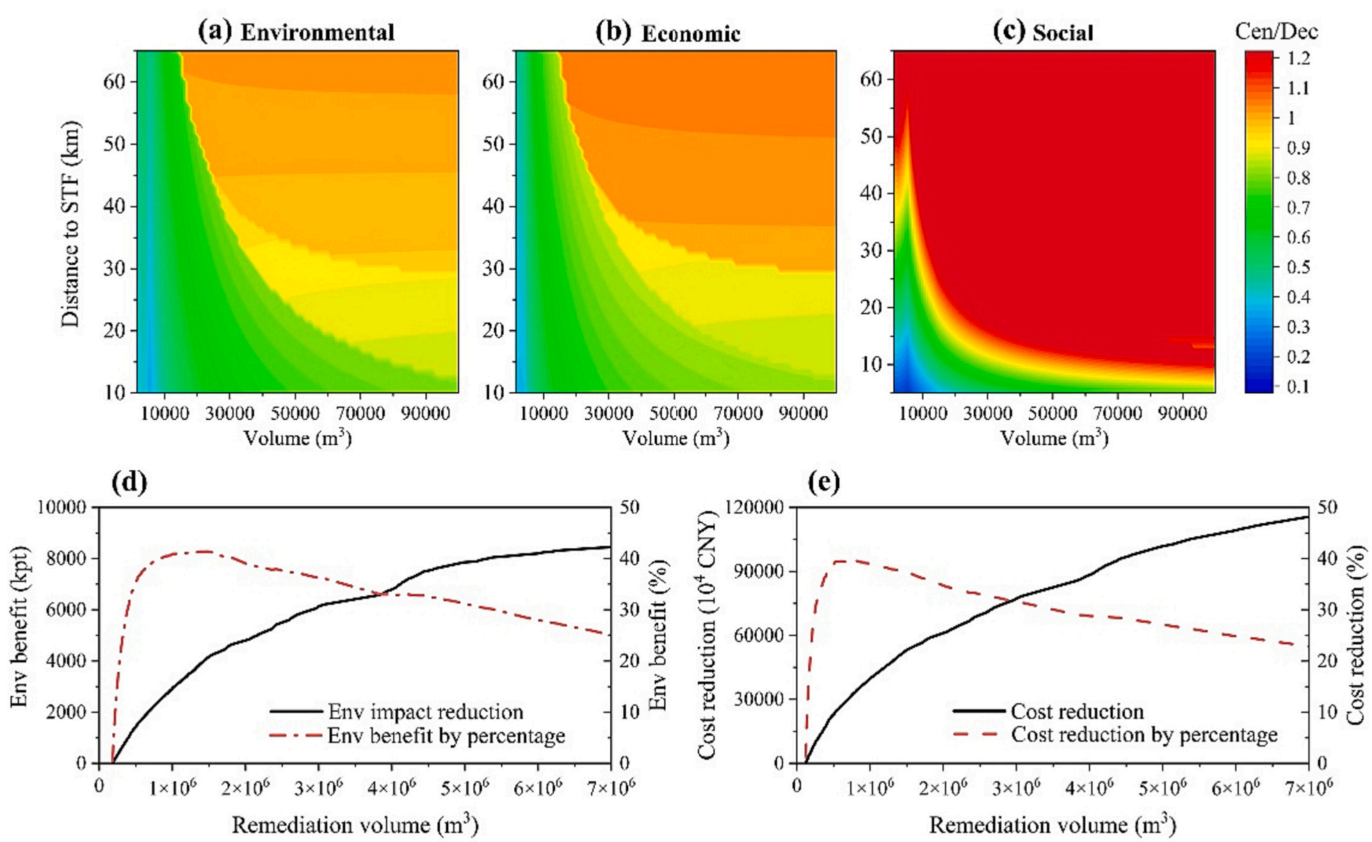

Fig. 8. Environmental (a), economic (b) and social (c) sustainability ratios of CEN compared to DEC from a single site perspective, and environmental (d) and economic (e) benefits of CEN scenario as a function of the amount of remediation of contaminated soil.

density of solid waste, brownfields, and so forth is more suitable for centralized strategies (Iglesias et al., 2012). A case study of contaminated sites cluster project in UK shows that reduction in 82 % of transport impact and 79 % in CO_2 emissions achieved through 14,000 m^3 of soil imported to STF (CL:AIRE, 2012).

3.5. Use of the developed framework in centralized remediation decision-making

For the first time, we developed an integrated framework of LCSA coupled with MOO to design and compare CEN and DEC strategies for multi-site remediation. The proposed framework can assist remediation decision-making at both site and regional scales by efficiently generating compromise solutions and visualizing the balance between the three pillars of sustainability under different scenario settings. The study results indicate that CEN strategies could be potentially desirable for metropolitan areas with large number of brownfields awaiting remediation and redevelopment. With the construction of STF(s), on-site construction activities and off-site disposal of contaminated soil could be significantly reduced, resulting in net environmental and economic benefits. Given that the increased transport impact could be a drawback of CEN strategies, it is recommended to comprehensively screen the possible remediation technologies and optimize soil transportation routes when applying the framework. If technically feasible, SW should be given priority for application in CEN scenarios.

It should be stressed that insights on the local site conditions are essential. The assumptions made in this study were based on limited investigations of sites in Zhuzhou City, and understandably, the assessment results would be city-specific or region-specific, since the soil texture, soil pollutants, distribution of sites, and treatment capacities will vary for each city or region across a country and around the world.

There are some limitations in this study. Firstly, to quantitatively compare the sustainability of CEN and DEC, some qualitative indicators were beyond the scope of this study. However, it is necessary to consider these factors in practice. For example, the soil reuse potential is often addressed in the sustainability assessment of contaminated site remediation (Holland et al., 2013; Li et al., 2022). S/S may greatly change the texture and constituents of the soil, and therefore limit its potential reuse as a resource. Landfilling completely eliminates the resource attribute of soil. Aside from the relatively low secondary impacts of SW, it also renders the benefit of soil recovery. Some quantitative social aspects such as community satisfaction, equality, and impacts on neighborhoods (Harclerode et al., 2015) may be of concern in the CEN scenario. These issues are often influenced by the NIMBY (Not In My Backyard) effect (Fredriksson, 2000; Sun et al., 2016)., and all stakeholders must be involved if a STF is going to be built. Secondly, the developed framework is a hierarchical optimization process: the determination of STF number and locations could be viewed as a problem of single-objective optimization and was carried out before the MOO. Nevertheless, it is worth noting that the constrains of STF number and locations may also be influenced by the parameters identified through MOO, and therefore, and therefore, may change over time. The optimization of facility numbers and locations has been widely studied in other fields, such as waste management, where it is considered a facet of reverse logistics (Bing et al., 2016). Various dynamic optimization approaches have been applied in reverse logistics (Kannan et al., 2009; Li et al., 2017; Zarbakhshnia et al., 2020), including genetic algorithm, artificial bee algorithm, colony particle swarm optimization, etc. These methodologies hold promise for addressing the STF optimization problem through an iterative procedure.

4. Conclusions

Soil remediation and further redevelopment of brownfields are challenges as well as opportunities for sustainable urban land use, and with the huge number of contaminated sites in cities around the world, there is a critical need to consider the design and optimization of remediation strategies at the city level. Centralized and decentralized treatment strategies have been studied in various fields, but limited research exists on soil remediation. This study built a method integrating LCSA and MOO to evaluate CEN and DEC for multi-site remediation, allowing for a straightforward comparison without biases under the condition that both scenarios were optimally designed. The main conclusions of the study results are:

- CEN scenario can reduce total environmental impacts by 25 %–41 % at the city level, and in particular, reduce global warming potential by 1.55×10^5 t CO_2eq. The CEN scenario can also reduce remediation life-cycle costs by 23 %–39 % (up to 176 million USD). These benefits mainly result from (1) increased application rate of SW, (2) reduced use of off-site disposal, and (3) reduction in construction input for and efficient utilization of STFs.
- The two scenarios each had its own advantages and disadvantages over social impact indicators. The CEN scenario had lower safety risks and worker wage, with a greater transport impact.
- The results of a sensitivity analysis suggest that CEN has significant advantages under various conditions. The transport distance was the most sensitive factor for social sustainability. The SW utilization rate and capital cost were sensitive for environmental and economic sustainability. The number and locations of STFs have a great impact on all three sustainability dimensions, which need to be carefully designed.

With the MOO of remediation design for CEN and DEC, the relative sustainability was visualized, and the net benefits of CEN were illustrated to support remediation decision-making. From a city or regional perspective, CEN has multiple advantages especially for industrial cities or regions with a large number of medium or small-sized contaminated sites. For an individual site, social impact would be a dominant factor in the remediation choice between CEN and DEC as the size of the site and the transport distance to an STF increase.

Recommendations for future research include: (1) incorporating more sustainability concerns into the framework by either broadening the system boundary or expanding the set of sustainability indicators; (2) developing a more comprehensive method to optimize STF number and locations; (3) validating and improving the methodology through the study of actual cases.

CRediT authorship contribution statement

Yinan Song: Investigation, Methodology, Writing – original draft. **Sihan Pan:** Investigation, Methodology, Writing – original draft. **Yuanliang Jin:** Investigation, Writing – original draft. **David O'Connor:** Investigation, Writing – original draft. **Paul Nathanail:** Supervision, Writing – review & editing. **Paul Bardos:** Supervision, Writing – review & editing. **Yang Kang:** Investigation, Writing – original draft. **Xiaoyong Zuo:** Investigation, Writing – original draft. **Hengyong Zhang:** Investigation, Writing – original draft. **Deyi Hou:** Data curation, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170908.

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