

**Quantitative sustainability assessment of *in situ* thermally enhanced
bioremediation for carbon efficient groundwater remediation**

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Abstract

In situ thermally enhanced bioremediation (ISTEB) is a promising approach for remediating contaminated soil and groundwater, yet comprehensive quantitative sustainability assessments of its sustainability remain scarce, especially for field-scale applications using hot water injection (TEB-HW) or thermal conductive heating (TEB-TCH). This study addressed this gap by developing the first fully quantitative sustainability framework integrating life cycle assessment (LCA) with best management practices (BMPs), comprising 108 indicators derived from extensive literature review and policy analysis. Using full-scale operational data from ISTEB implementations, we quantified the environmental, economic, and social performance of TEB-HW and TEB-TCH relative to conventional thermal treatment (TCH only). Results show that compared with TCH only, TEB-HW and TEB-TCH reduced carbon emissions by 78% and 31%, and achieved cost savings of 72% and 38%, while also improving community engagement and satisfaction. Normalized multi-criteria sustainability scores indicate overall performance gains of 31% and 13% compared to TCH only. Further optimization of BMPs, such as electric vehicle transport, green injectates, and renewable energy integration, could enhance ISTEB sustainability by up to 45%. These findings provide novel evidence for the practical viability and environmental benefits of ISTEB, offering actionable strategies for low-carbon, cost-effective, and socially acceptable remediation that align with sustainable production principles and contribute toward global net-zero carbon goals in contaminated site management.

Keywords: Sustainable remediation, Life cycle assessment, Best Management Practices, Thermally enhanced bioremediation, Green/low carbon remediation

Abbreviation	Description
BMPs	Best management practices
Ep	Environmental points
EPA	Environmental protection agency
EVs	Electric vehicles
FE	Freshwater ecotoxicity
FPM	Fine particulate matter formation
FRS	Fossil resource scarcity
GSR	Green and sustainable remediation
GWP	Global warming potential
HCT	Human carcinogenic toxicity
HNCT	Human non-carcinogenic toxicity
ISB	<i>In situ</i> bioremediation
ISO	International organization for standardization
ISTEB	<i>In situ</i> thermally enhanced bioremediation
ISTT	<i>In situ</i> thermal treatment
LCA	Life cycle assessment
mbgs	meter below ground surface
MCA	Multi criteria analysis
MRS	Mineral resource scarcity
NZC	Net-zero carbon emission
PHCs	Petroleum hydrocarbons
SDG	Sustainable development goal
SuRF	Sustainable remediation forum
TE	Terrestrial ecotoxicity
TEB-HW	Thermally enhanced bioremediation coupled with hot water injection
TEB-TCH	Thermally enhanced bioremediation coupled with thermal conductive heating
WC	Water consumption

1 Introduction

Soil and groundwater contamination pose severe threats to global food security, ecosystems, and human health (Coulon et al., 2016, Hou et al., 2020, Chen et al., 2025). Over five million contaminated sites have been identified globally, with numbers continuing to increase, highlighting the urgent need for remediation interventions (Hou et al., 2023). Among remediation technologies, *in situ* thermal treatment (ISTT) is one of the most widely used remediation technologies (Ding et al., 2019). However, our earlier study demonstrated that despite its effectiveness, ISTT exhibits relatively poor sustainability in terms of cost and carbon emissions (Yang et al., 2024). This stands in contrast to the principles of Sustainable Development Goal 12 (SDG 12), which calls for sustainable consumption and production patterns through improved resource efficiency and reduced environmental footprints (Chen et al., 2025). In contrast, *in situ* bioremediation (ISB) is recognized as a more sustainable approach, offering cost-effectiveness, environmental compatibility, and minimal disruption to soil (Wethasinghe et al., 2006, Abbas et al., 2020, Zeng et al., 2023). Yet, its adoption is hindered by low remediation efficiency, long treatment durations, particularly in countries with urgent brownfield redevelopment needs (e.g., China) (Wang et al., 2022). To address these limitations, *in situ* thermally enhanced biodegradation (ISTEB) has been developed as a promising remediation strategy that integrates the thermal input of ISTT with the biodegradation capability of ISB (Luo et al., 2025). This combined approach mitigates high energy demand and low efficiency issues and more closely aligns with SDG 12's emphasis on clean, efficient technologies for sustainable pollution control and resource use (Paleologos et al., 2025).

Temperature is a key factor influencing ISTEB performance. Moderate thermal stimulation can enhance contaminant bioavailability and microbial metabolic activity, thereby accelerating degradation rates (Antizar-Ladislao et al., 2007). For example, increasing temperatures from 10°C to 30°C increased by 10-fold the microbial degradation rates of trichloroethylene (TCE) (Friis et al., 2007), improved benzene biodegradation from 57% to 89%, and enhanced benzo[a]pyrene (BaP) degradation from 16% to 35% (Ali et al., 2023). ISTEB can be implemented via various heating methods (Wang et al., 2022). Thermally conductive heating coupled with TEB (TEB-TCH) is commonly used in low-permeability silt or clay aquifers, achieving subsurface temperatures of 30-40 °C and synergistically enhancing the remediation of chlorinated hydrocarbons and petroleum

hydrocarbons (Friis et al., 2005, Moradi et al., 2018). *In situ* hot water injection (TEB-HW) uses clean energy sources (e.g., natural gas, solar) to rapidly elevate groundwater temperatures through heat exchange, offering efficient heating of high-permeability aquifers while reducing reliance on energy-intensive systems. For instance, a groundwater circulation system developed by (Nemecek et al., 2018) raised subsurface temperatures to 30 °C, achieving TCE concentrations below remediation targets within five months.

Despite being a promising remediation strategy, a significant research gap remains in the comprehensive sustainability quantification of ISTEb. Although the technology is conceptually aligned with green and sustainable remediation (GSR) and carbon neutrality goals, its environmental, economic, and social sustainability remains poorly quantified (Celletti et al., 2025). This gap restricts the alignment of remediation practices with SDG 12. Current sustainability evaluations are often fragmented. Most studies primarily rely on quantitative life cycle assessment (LCA) methods to evaluate environmental impacts (Jin et al., 2021, Liang et al., 2023, Xu and Hou, 2025), whereas the economic and social assessments are generally semi-quantitative or qualitative, introducing additional uncertainty and potential bias (Song et al., 2018). As a result, previous work frequently addresses only a single sustainability dimension or provides descriptive best management practices (BMPs) without integrated quantifiable metrics (Xiao et al., 2024). For instance, while existing LCA studies offer valuable environmental profiles, they rarely incorporate economic and social indicators into a unified scoring framework (Liu et al., 2025). This methodological inconsistency, coupled with the absence of a holistic and fully quantitative evaluation framework, hinders a rigorous comparison of ISTEb with other remediation alternatives, obscures its contribution to NZC targets, and ultimately limits its optimized deployment and policy uptake.

To address this gap, this study (1) developed a fully quantitative sustainability assessment framework for ISTEb; (2) implemented TEB-HW and TEB-TCH at a petroleum hydrocarbon-contaminated site, collecting full-scale operational data to validate the framework and quantify the sustainability of the 2 approaches; and (3) proposed targeted measures to further enhance sustainability and support progress towards NZC in future applications. Collectively, this work provides a critical tool and actionable insights for remediation practitioners, policymakers, and researchers, facilitating the strategic adoption of ISTEb as a verifiably sustainable remediation

technology.

2 Sustainability assessment indicators, framework and methods

2.1 Assessment indicators and framework

Through an extensive review of both literatures and policy documents, we compiled and summarized the existing sustainability assessment indicators related to site remediation, and subsequently developed the ISTEb sustainability assessment framework, as illustrated in Fig. 1. The compilation of indicators comprised two main components: (1) a literature review and (2) a policy review. For the literature review, we searched the Web of Science (WOS) Core Collection database using the keywords “sustainability assessment” and “contaminated remediation,” covering the period from 2010 to 2024. This initial search yielded 180 relevant articles. After a rigorous screening process, 36 papers containing specific sustainability indicators were selected for further analysis. For the policy review, we identified and examined five policies or standards that incorporate sustainability assessment indicators, issued by the U.S. EPA, ASTM International, the UK Sustainable Remediation Forum (SuRF-UK), and the China Sustainable Remediation Forum (SuRF-CN). Detailed descriptions and the complete list of the selected articles and policies are provided in Table S1.

A comprehensive quantitative assessment framework was developed by integrating LCA with best management practices (LCA-BMPs), which encompassed environmental, economic, and social sustainability assessment indicators, each with multiple sub-indicators. Environmental sustainability was evaluated using LCA (Hossain et al., 2020), a widely adopted approach for quantifying environmental impacts of physical (Liang et al., 2023), chemical (Hou et al., 2016), and coupled remediation technologies (Yang et al., 2024) at contaminated sites. The detailed LCA method is described in Section 2.2. The economic and social impacts were assessed through BMPs implementation across the entire ISTEb process. BMPs were established based on the screening method of Yang et al. (2023) with the goals of optimizing natural resource conservation, safeguarding human health, and minimizing economic costs via relatively simple and mutually beneficial actions, thus improving remediation sustainability. The specific evaluation methods are provided in Section 2.3. To enable systematic comparison of the different remediation technologies, multi criteria analysis (MCA) was applied to standardize environmental, economic, and social

sustainability impacts (Alvarez-Guerra et al., 2009, Sondergaard et al., 2018), with detailed calculations provided in Section 2.4.

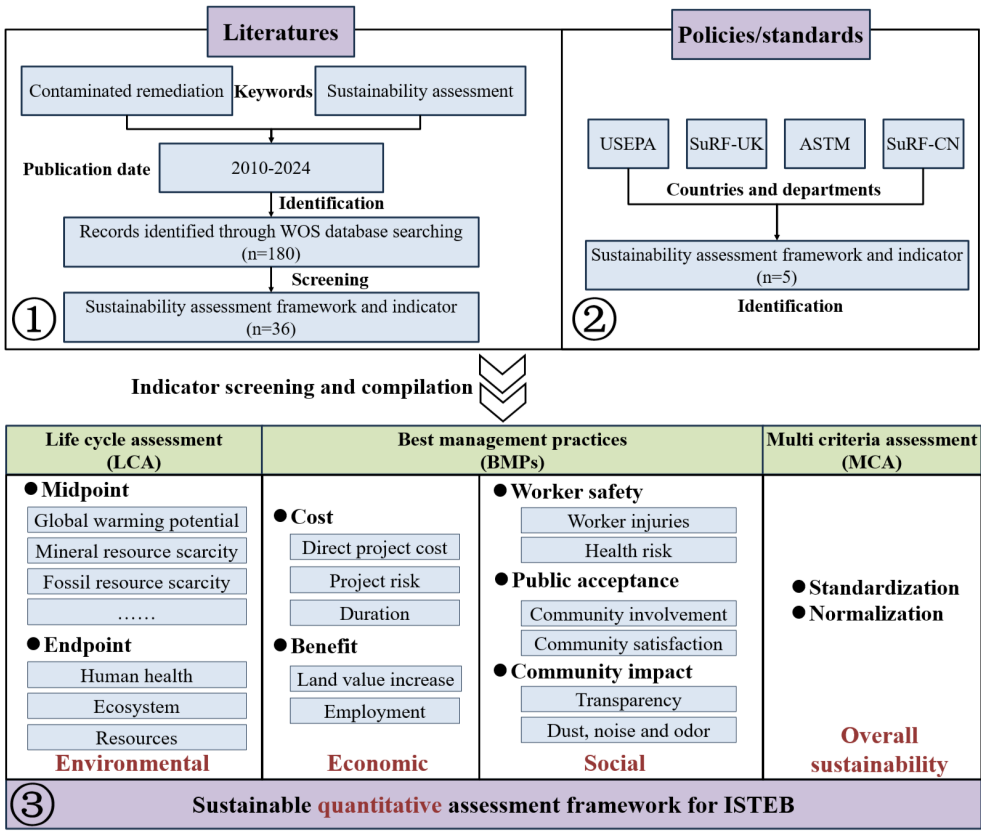


Fig. 1. Indicators screening/compilation and development of the ISTEb sustainability assessment framework

2.2 LCA for environmental impacts

2.2.1 LCA goal, scope, and functional unit

To quantify the environmental impacts of the entire remediation process for TEB-HW, TEB-TCH, and TCH-only, LCA was conducted in accordance with the international standards ISO 14040 and ISO 14044 (Karatum et al., 2018, Foerster et al., 2024). A functional unit of “remediating 1 m³ of contaminated saturated aquifer to meet the cleanup goals” was used, with all environmental impact results normalized to this unit. The LCA boundary covered the entire remediation life cycle, from project initiation to completion (Fig. 2), and was divided into four phases (Ni et al., 2020) as follows: (1) material acquisition, (2) construction, (3) operation, and (4) end-of-life activities. Consistent with the ISO standards' requirements for cut-off criteria and data quality, processes such as large-scale equipment manufacturing, sampling, and material recovery were excluded from the inventory due to insufficient reliable data (Hou et al., 2014).

2.2.2 Life cycle inventory and impact assessment

The life cycle inventory was developed using field data collected during the full-scale remediation operations, ensuring data accuracy and representativeness. The material acquisition included inputs such as well materials, heating and injection system and transportation. The construction phase covered drilling, well installation, and site preparation. The operation phase accounted for electricity, energy, and water consumption, while end-of-life activities included well backfilling and waste disposal. Upstream inputs were sourced from the Ecoinvent 3.9.1 database to develop a comprehensive life cycle model ([Ding et al., 2022](#), [Simaitis et al., 2025](#)).

All life cycle inventory data in this study were obtained directly from field measurements to minimize uncertainties associated with hypothetical or assumed values. Since the remediation activities were implemented at three adjacent treatment zones, consistency in all collected data was ensured. To guarantee transparency, accuracy, and reliability of data and results, we systematically tracked and documented material flows, energy consumption, and BMPs data throughout the implementation process across the entire system boundary. Detailed quantitative records are presented in Tables S2-S4. Material consumption data (including bentonite, well pipes, injectates and steel) were sourced from verified procurement contracts. Energy consumption metrics, including electricity, fuel oil, natural gas, and others, were obtained through authenticated and real-time on-site energy logs. BMPs implementation data were collected through direct observation and field verification to ensure full compliance with BMPs calculation requirements.

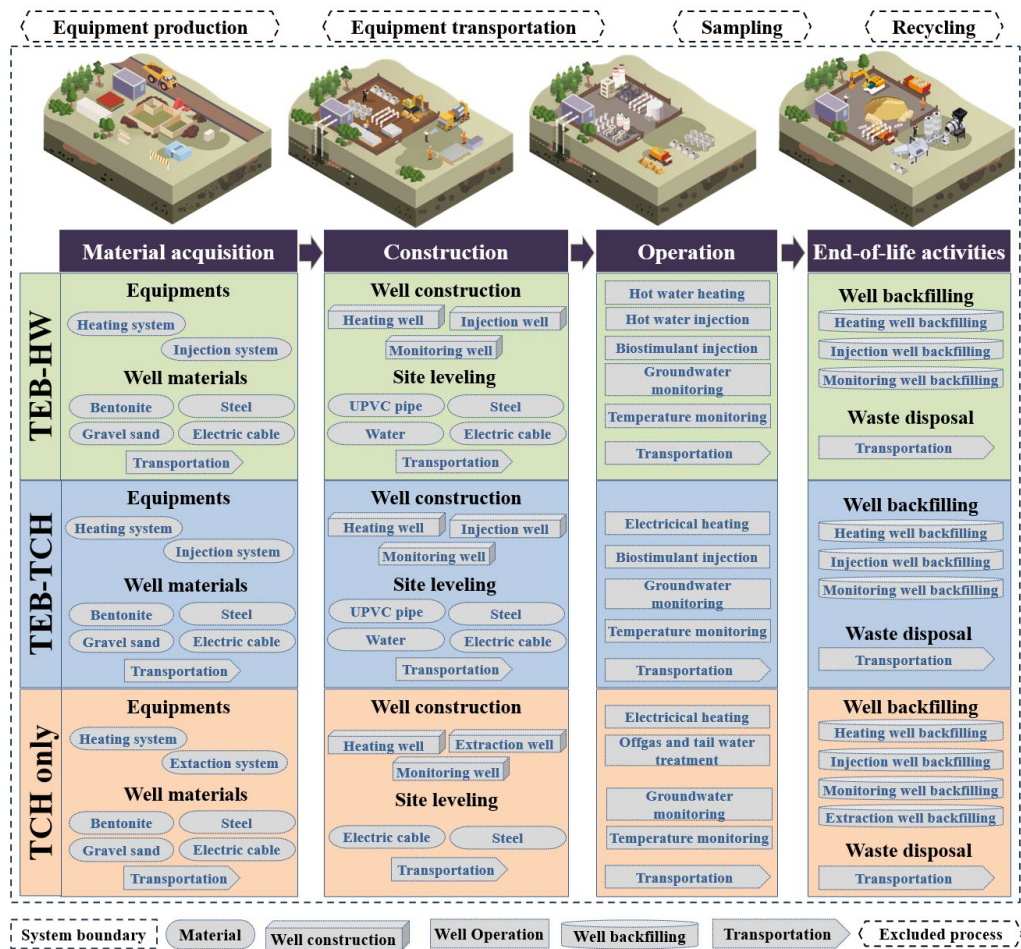


Fig. 2. The boundary of LCA for TEB-HW, TEB-TCH and TCH only

The environmental impacts of TEB-HW, TEB-TCH and TCH only were quantified using SimaPro software with the ReCiPe 2016 method (Song et al., 2018), evaluating both midpoint and endpoint indicators (Fig. 1). The midpoint indicators included global warming potential (GWP, kg CO₂ eq), human carcinogenic toxicity (HCT, kg 1,4-DCB), human non-carcinogenic toxicity (HNCT, kg 1,4-DCB), fine particulate matter formation (FPM, kg PM_{2.5} eq), terrestrial ecotoxicity (TE, kg 1,4-DCB), freshwater ecotoxicity (FE, kg 1,4-DCB), mineral resource scarcity (MRS, kg Cu eq), fossil resource scarcity (FRS, kg oil eq) and water consumption (WC, m³). These midpoint results were integrated into three endpoint categories (human health, ecosystem, resources), and were ultimately standardized as environmental points (Ep) for unified comparison (Yang et al., 2024).

2.2.3 Sensitivity analysis

A sensitivity analysis was performed to assess how different environmental management scenarios influence the environmental sustainability outcomes (Briones-Hidrovo et al., 2022). The sensitivity of environmental impacts of TEB-HW, TEB-TCH and TCH only were compared under different

transportation distance, injectates and electricity consumption scenarios.

2.3 BMPs for economic and social impacts

The sustainable benefits derived from the implementation of BMPs not only minimized environmental footprints but also yielded significant economic and social advantages. This indicates that standardizing BMPs design can enhance the overall sustainability of remediation technologies. The U.S. EPA has identified five core BMPs during Superfund site implementations to improve the green sustainability of bioremediation (EPA, 2021): (1) reducing total energy consumption while increasing the share of renewable energy, (2) minimizing emissions of air pollutants and greenhouse gases, (3) decreasing water use while safeguarding water quality, (4) promoting resource conservation and waste reduction, and (5) protecting land resources and ecosystems. Meanwhile, the SuRF-UK initiative has established a tailored set of BMPs specifically for bioremediation, underscoring the critical importance of complying with BMP requirements throughout remediation activities (SuRF-UK, 2021).

Through comprehensive policy and literature review, we developed 108 BMPs spanning the entire life cycle of remediation—from remediation design to site reuse—for HW-TEB, TCH-TEB, and TCH-only scenarios, the full list of BMPs are provided in Table S5. In the calculation, the maximum value for each economic and social sustainability indicator derived from BMPs was set to 5, and the minimum value was set to 0. If all relevant BMPs were fully implemented during the remediation process, the indicator score was assigned the maximum value of 5. If BMPs were only partially implemented, the indicator score was calculated proportionally based on the number of BMPs executed. The calculation formula is as follows:

$$S_2 = \frac{S_1}{M_a} \times M \quad (1)$$

where S_1 is the benchmark value, set at 5; S_2 represents the economic and social sustainability score, ranging between 0 and 5; M_a denotes the total number of applicable BMPs; and M refers to the number of BMPs implemented in the field. Project direct cost and remediation duration were used as indicators for economic sustainability, while the incidence of worker injuries served as a social sustainability metric, all collected according to actual field conditions. Additional economic and social indicators, such as remediation transparency, community participation, and satisfaction, were

quantitatively assessed based on BMPs implementation.

2.4 Overall sustainability assessment based on MCA

MCA enables the integration of quantitative environmental, economic, and social results into a comprehensive sustainability score for comparing remediation alternatives (Sondergaard et al., 2018). In the calculation process, a two-stage normalization procedure was employed. First, sub-indicators within each sustainability dimension (environmental, economic, and social) were individually normalized, with the sum of weights for the sub-indicators in each dimension set to 1, and weights distributed equally among the sub-indicators within that dimension. Specifically, the environmental sustainability category consists of three endpoint indicators: resources, ecosystem, and human health, each assigned a weight of 0.33. The economic sustainability category includes six indicators: worker injuries, health risk, community satisfaction, community involvement, dust, noise and odor, and Transparency, each assigned a weight of 0.16. The social sustainability category comprises five indicators: direct project cost, project risk, duration, land value increase, and employment, each assigned a weight of 0.2. In the second stage, the three overarching sustainability categories were normalized concurrently to generate the final composite result. The weights for these three primary categories were equally assigned at 0.33 each, reflecting the core objective of sustainable remediation, to achieve synchronized and coordinated development across environmental, economic, and social dimensions (Hou et al., 2023). The sustainability score is calculated as follows:

$$S_3 = \sum \left(\frac{IV}{IV_{max}} \times W \right) \times 100 \quad (2)$$

here, S_3 represents the overall sustainability score, which ranges from 0 to 100 (a higher value denotes greater sustainability). IV is the value of a sustainability sub-indicator; IV_{max} is the maximum value for that sub-indicator across all alternatives, and W is the assigned weight of the sub-indicator.

2.5 Data collection for sustainability assessment

2.5.1 Sites characterization

The study site was a petroleum refinery in Qingyang City, Gansu Province, China (Fig. 3a), which had produced gasoline and diesel fuels for over four decades (Zhang et al., 2025). The site exhibited typical Loess Plateau geological characteristics, consisting of layers of miscellaneous fill, silty sand,

gravels and bedrock (Fig. 3b). The groundwater was encountered at depths of ~6.5-7.5 m below ground surface (mbgs), predominantly within silty and gravel strata with the effective porosity estimated to be 0.30-0.40 (Chapuis, 2004) (Fig. 3b). The main contaminants of concern were petroleum hydrocarbons (PHCs), with benzene frequently exceeding groundwater quality standards (0.2-0.9 mg/L) and total PHC concentrations ranging from 1.46 to 64.9 mg/L. Contaminants were detected in groundwater to the depths of ~9.5 mbgs, and no contaminant exceedances were detected in the bedrock. The site was surrounded by residential areas and farmland and is designated for industrial land redevelopment after remediation.

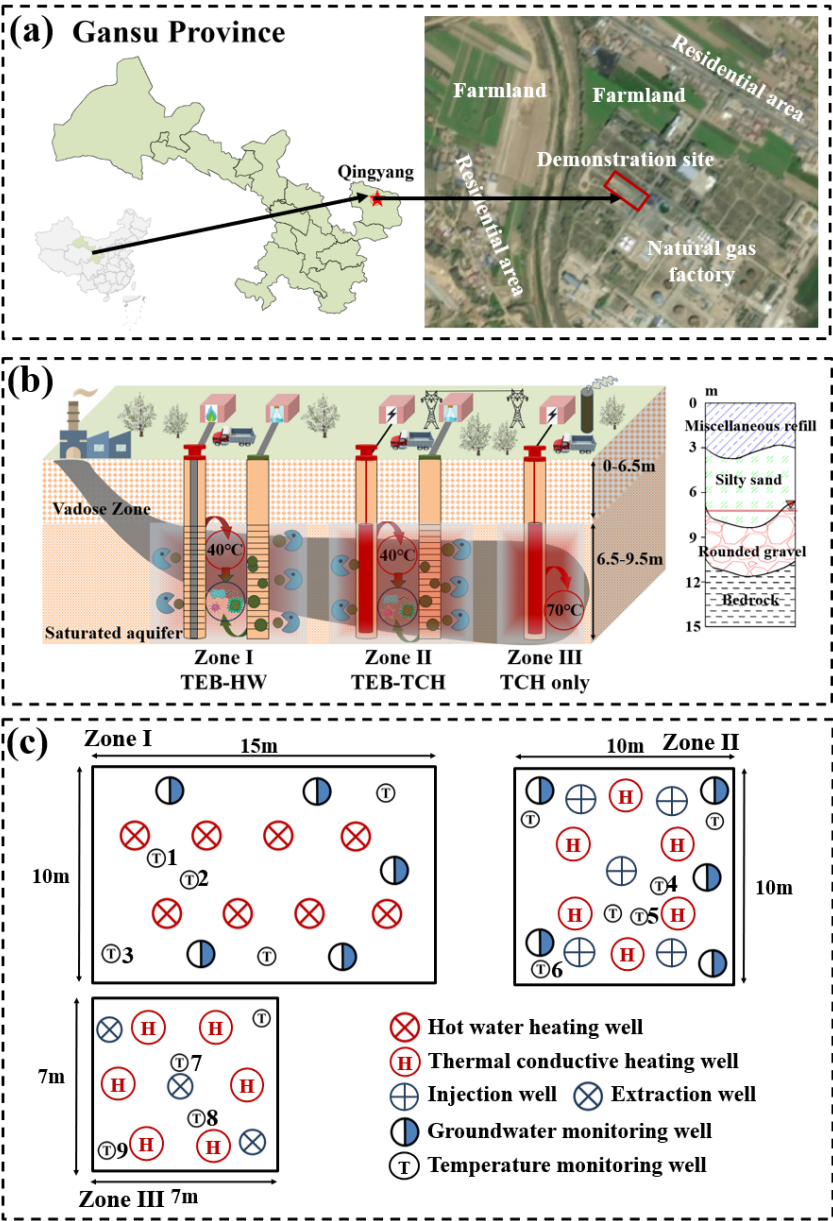


Fig. 3. Contaminated sites characterization: (a) geographical location, (b) conceptual model of TEB-HW, TEB-TCH and TCH only, (c) wells layout in the study area.

2.5.2 Pilot-scale field trials

Three adjacent treatment zones, TEB-HW zone, TEB-TCH zone, and TCH only zone, were set up to evaluate the remediation performance and sustainability of these 3 technologies under comparable hydrogeological conditions and contamination conditions. The conceptual design and well layout are shown in Fig. 3. The target temperature was set at 40°C for the TEB-HW and TEB-TCH zones to optimize microbial activities, and at 70°C for the TCH-only zone. The remediation depth across all zones was between 6.5-9.5 mbgs.

As shown in Fig. 3c, the TEB-HW zone covered 150 m² and the total remediation volume of 450 m³. Eight hot water heating wells were installed in a double-row triangular configuration with a 3 m spacing. These wells served for both heating and biostimulant injection. Five groundwater monitoring wells and five temperature monitoring wells were installed at 1 m and 2 m offsets. Water heated to 70 °C by natural gas boilers was mixed with magnesium sulfate and injected under pressure, achieving uniform subsurface heating to 40 °C within 10 days. Bi-monthly sampling was conducted over five monitoring cycles until remediation targets were met. The TEB-TCH zone encompassed 100 m², yielding a total remediation volume of 300 m³. Six heating wells arranged hexagonally and five injection wells were interspaced between them. Five groundwater monitoring wells and five temperature monitoring wells were installed around and between heating wells. The subsurface was pre-heated to 40°C over 60 days via thermal conduction heating, followed by magnesium sulfate injection to stimulate thermally enhanced biodegradation. Sampling and monitoring procedures mirrored those of the TEB-HW zone. The TCH only zone covered 49 m² with a depth of 6.5-9.5 m, resulting in a total remediation volume of 147 m³. Six heating wells configured hexagonally and three extraction wells surrounding them for vapor-phase recovery were installed. Four temperature monitoring wells were located near the heating wells and along the boundary. Continuous thermal conduction heating raised subsurface temperatures to 70°C over 90 days, followed by exhaust gas treatment. The total remediation duration was six months.

3 Results and discussion

3.1 Environmental impacts of TEB-HW, TEB-TCH and TCH only zones

3.1.1 Temperature changes in different remediation zones

Subsurface temperature distribution was a critical parameter influencing both the biodegradation of

organic contaminants and overall energy consumption (Kaur et al., 2021, Zeng et al., 2023), making it a pivotal factor in the sustainability of ISTEb. As shown in Fig. 4, the TEB-HW zone achieved the target temperature of 40°C by day 8, approximately 30 days earlier than TEB-TCH, with a total natural gas consumption of 356 m³. Subsequent monitoring over the following three months, the temperature remained stable around 30°C, except for a localized cold spot (TW-3). In contrast, TEB-TCH reached 40°C by day 38, while the TCH-only zone required nearly 5 months to attain 70°C. The rapid temperature increase facilitated by hot water injection demonstrates its superior thermal efficiency. All three zones met cleanup targets for COC upon field trial completion, confirming that TEB-HW and TEB-TCH are well-suited for remediating low to moderate concentrations of organic contaminants compared to TCH only.

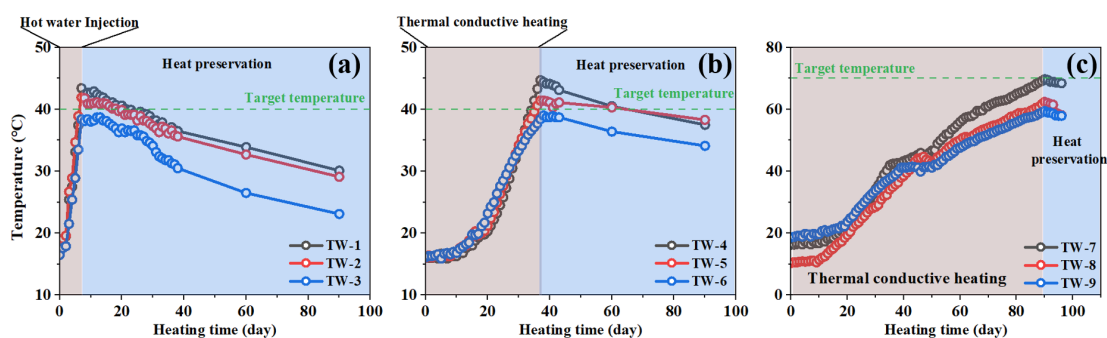


Fig. 4. Subsurface temperature evolution at the depth of 7 mbgs: (a) TEB-HW, (b) TEB-TCH, (c) TCH only (Note: TW-1~9 locations in Fig. 3c)

3.1.2 LCA midpoint results

The midpoint results for the three remediation zones across the four phases are shown in Fig. 5. In the TEB-HW zone (Fig. 5a), the material acquisition phase contributed to 40% of the total impacts on global warming potential (GWP), fossil resource scarcity (FRS) and human carcinogenic toxicity (HCT). The operational phase dominated the impacts on GWP, FPM, TA, TE, and HNCT, each exceeding 40%, while water consumption (WC) impacts exceeded 80%. In contrast, both TEB-TCH (Fig. 5b) and TCH only zone (Fig. 5c) showed higher material acquisition impacts on mineral resource scarcity (MRS) and HCT relative to TEB-HW. During the operational phase, their GWP, FPM, and TA were significantly greater than those observed in TEB-HW, all exceeding 60% of the total impact. The end-of-life phase contributed negligibly to overall impacts across all three zones.

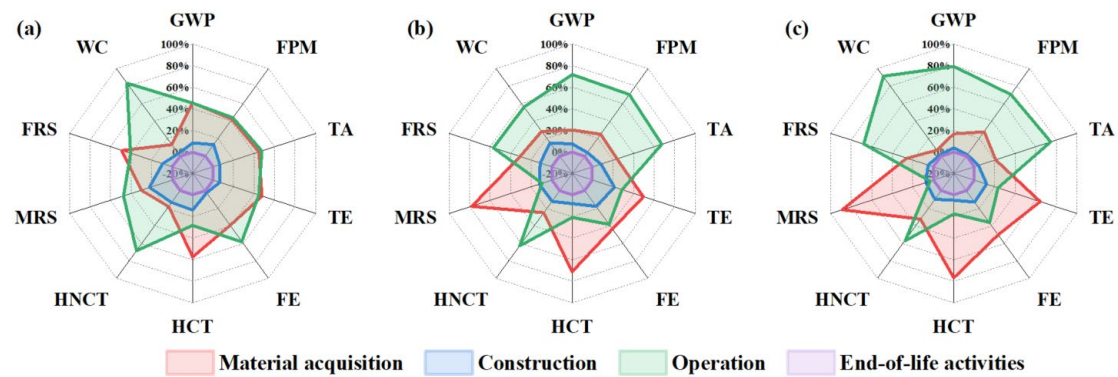


Fig. 5. Midpoint environmental sustainability results for: (a) TEB-HW, (b) TEB-TCH, (c) TCH only zone. Note: Global warming potential (GWP, kg CO₂ eq), Human carcinogenic toxicity (HCT, kg 1,4-DCB), Human non-carcinogenic toxicity (HNCT, kg 1,4-DCB), Fine particulate matter formation (FPM, kg PM_{2.5} eq), Terrestrial ecotoxicity (TE, kg 1,4-DCB), Freshwater ecotoxicity (FE, kg 1,4-DCB), Mineral resource scarcity (MRS, kg Cu eq), Fossil resource scarcity (FRS, kg oil eq) and Water consumption (WC, m³)

To identify specific sources of environmental impacts, subphase-level contributions were analyzed (Yang et al., 2024). The relative contributions of each subphase to environmental midpoint indicators for TEB-HW, TEB-TCH, and TCH-only are shown in Fig. 6 with detailed data in Tables S3-S5. For TEB-HW, the main impact contributors were transportation, injectates (magnesium sulfate), and construction materials. Transportation accounted for >80% of HCT, and > 50% of TE, FE, TA, FRS, FPM and GWP. This was largely due to the emission of sulfur-containing exhaust gases and nitrogen oxides during fuel combustion (Bicer and Dincer, 2018). The injectates contributed the most to HNCT (65%), FE (37%) and TE (23%), due to their irritating effect on human skin, mucous membranes, and respiratory tracts, with prolonged exposure potentially leading to central nervous system suppression (Egbueri, 2023). Their impact on other environmental indicators, such as GWP, FPM, MRS and TA, ranged between 20% and 40%. Site construction materials accounted for 20% of the impact on MRS and 11% on HCT. This was due to the extensive unplasticized polyvinyl chloride (UPVC) pipeline deployment and steel usage in TEB-HW implementation. The UPVC manufacturing process generated fine particulate matter, a key contributor to human toxicity (Ye et al., 2017). Additionally, the raw materials of steel directly drove depletion of non-renewable mineral resources (Wang et al., 2023). Hot water use dominated water consumption (67%), whereas drilling, electricity, and natural gas use (250 kWh and 356 m³, respectively) had negligible effects.

For TEB-TCH, the most significant environmental impact sources were electricity consumption, well construction materials, and transportation (Fig. 6b). Heating electricity consumption was a major contributor to GWP (65%), FPM (62%), TA (58%), FRS (48%), and WC (43%). Given that >60% of China's electricity was fossil fuel-based in 2023 (CSY, 2022), this phase was a major source of PM_{2.5} and CO₂ emissions. Site construction materials contributed 71% to MRS, primarily due to the reliance on mineral resources for the steel used in constructing heated well casings. Transportation effects on HCT mirrored those of TEB-HW, dominated by SO_x and NO_x emissions. However, transportation contributed less to GWP and FPM than in TEB-HW, indicating electricity consumption as the main driver. Injectates contributed moderately to HNCT (33%), FE (18%), and TE (11%).

As with TEB-TCH, the most significant environmental impacts of TCH-only arose from heating electricity consumption, the materials used for well construction, and transportation (Fig. 6c). However, compared to TEB-TCH, the impacts from heating electricity consumption and well construction materials were more pronounced, while the impact from transportation was slightly reduced. Mainly due to the electricity consumption was more than double that of TEB-TCH.

The overall comparison (Fig. 6d) shows that, except for water consumption, TEB-HW exhibited substantially lower environmental impacts than both TEB-TCH and TCH-only. Specifically, TEB-HW reduced GWP, TA, FPM, and MRS by 75% compared to TEB-TCH and by >60% across all categories compared with TCH-only, achieving 80% reduction in GWP, WC, MRS, and FPM. This was due to two factors: (1) 99% lower energy demand (0.5 kWh/m³ for TEB-HW vs. 37.9 kWh/m³ for TEB-TCH vs. 79.7 kWh/m³ for TCH-only), reducing air-related quality indicators such as GWP, FPM and TA; and (2) fewer wells and associated materials, substantially lowering ecological and human health toxicity impacts. The reduction in energy and material consumption levels demonstrated that the application of TEB-HW can significantly contribute to the achievement of SDG 12.

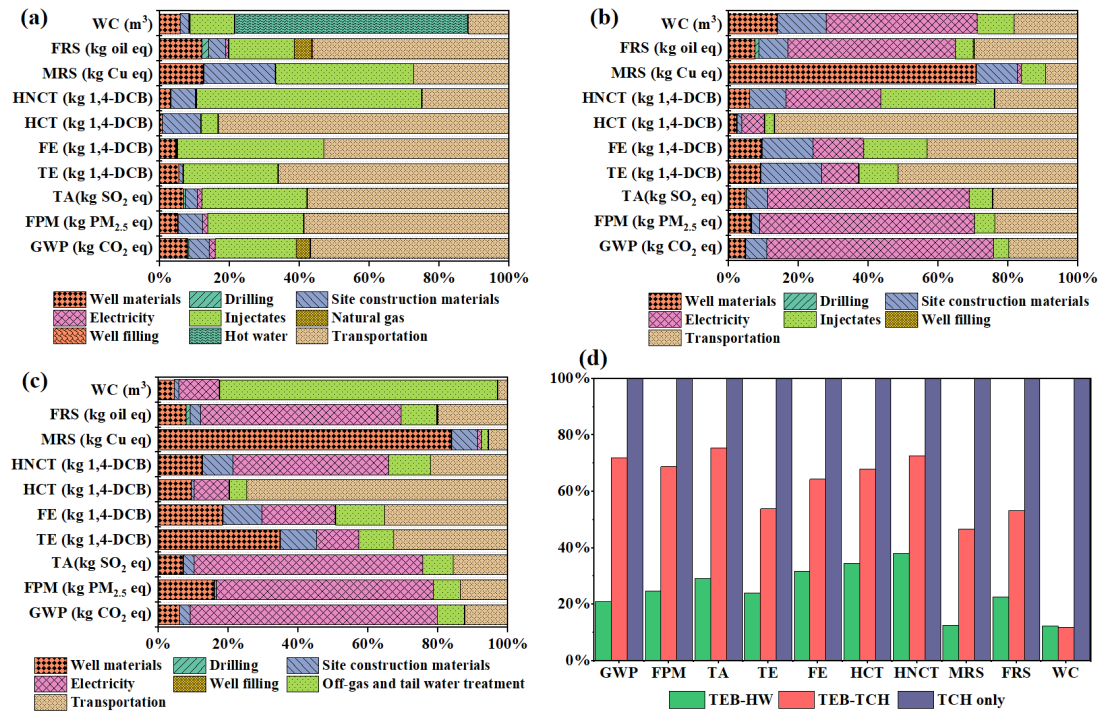
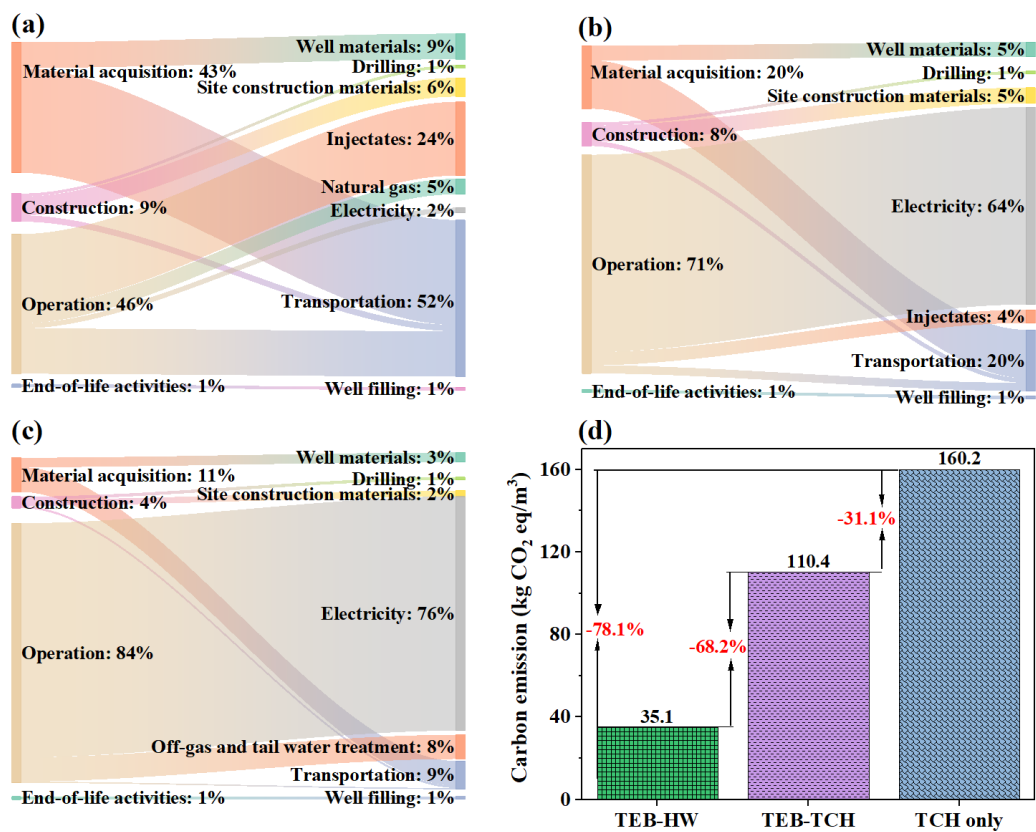


Fig. 6. Detailed environmental results of three remediation zones: (a) TEB-HW, (b) TEB-TCH, (c) TCH only, (d) Comparison of midpoint indicators for TEB-HW, TEB-TCH and TCH only zone. Note: Global warming potential (GWP, kg CO₂ eq), Human carcinogenic toxicity (HCT, kg 1,4-DCB), Human non-carcinogenic toxicity (HNCT, kg 1,4-DCB), Fine particulate matter formation (FPM, kg PM_{2.5} eq), Terrestrial ecotoxicity (TE, kg 1,4-DCB), Freshwater ecotoxicity (FE, kg 1,4-DCB), Mineral resource scarcity (MRS, kg Cu eq), Fossil resource scarcity (FRS, kg oil eq) and Water consumption (WC, m³)

3.1.3 Carbon emissions and pathways

The carbon emission flows for the three zones are shown in Fig. 7. For TEB-HW (Fig. 7a), carbon emissions across the four life-cycle phases were ranked as follows: (1) operation (46%) > (2) material acquisition (43%) > (3) construction (9%) > (4) end-of-life activities (1%). Sub-phase analysis showed that transportation was the largest contributor (52%), followed by injectates use (24%), while all other sub-phases contributed to <10%. Notably, carbon emissions from energy consumption (electricity and natural gas) accounted for < 5% of the total emissions, highlighting TEB-HW low reliance on energy-intensive resources. In TEB-TCH (Fig. 7b) and TCH only (Fig. 7c) zones, the operation phase dominated emissions contributing 71% and 84%, respectively, while material acquisition contributed 20% and 11%. Construction and end-of-life phases remained <10% in both cases. For TEB-TCH, electricity consumption during operation accounted for 64% of emissions, followed by transportation at 20%, with all other subphases <6%. In the TCH-only zone, electricity and transportation contributed 76% and 9%, respectively, with remaining subphases <

370 8%.



371
372 **Fig. 7.** Carbon emission pathway for all phases and sub-phases for (a) TEB-HW, (b) TEB-TCH, (c) TCH only and
373 (d) Comparison of carbon emissions for remediation of 1m³ contaminated soil and groundwater by TEB-HW, TEB-
374 TCH and TCH only

375 The carbon emissions per unit volume of contaminated soil and groundwater (Fig. 7d) were 10.9
376 kg/m³ for TEB-HW, 74.4 kg/m³ for TEB-TCH, and 153.4 kg/m³ for TCH-only. Compared to TEB-
377 TCH and TCH only, TEB-HW achieved a carbon reduction of 85% and 93%, respectively,
378 demonstrating significant potential for carbon mitigation potential. These results confirm that
379 energy-intensive operations are the primary emission driver, consistent with [Hu et al. \(2011\)](#)
380 emphasizing the importance of optimizing energy-use to enhance the sustainability of thermal
381 technologies.

382 3.1.4 LCA endpoint impacts and sensitivity analysis

383 Using environmental points (Ep) as the composite metric, the midpoint environmental impacts were
384 normalized to the endpoint indicators ([Yang et al., 2024](#)), where lower Ep value indicates greater
385 sustainability (Fig. 8a). The TEB-HW zone demonstrated superior environmental performance with
386 an endpoint result of 0.29 Ep, representing 73% and 88.3% reductions compared to TEB-TCH (1.06

Ep) and TCH only (2.48 Ep) zones, respectively. Specifically, TEB-HW consistently showed lower impacts across human health, ecosystems, and resources, with the largest improvement observed in human health.

The sensitivity analyses on carbon emissions of three remediation zones are shown in Fig. 8b. The baseline conditions refer to the results obtained in the current study (See section 3.1.3). Transportation distance, injectate usage, and electricity consumption were identified as key variables. For TEB-HW zone, variations in electricity consumption had minimal impact whereas transportation distance was the dominant driver: halving the distance reduced emissions by 26%, while doubling it increased emissions by 53%. Injectate variations had a smaller influence. For TEB-TCH and TCH-only zones, electricity consumption was the primary driver: halving consumption reduced emissions by >30%, while doubling it increased emissions by >60%, whereas transportation distance contributed <20% variation.

To further evaluate mitigation potential, conventional diesel freight was compared with electric vehicles (EVs), consistent with global decarbonization trends. In the EVs scenario, we calculated the environmental impacts by replacing the fuel consumption for 1 km transportation with an electricity consumption of 0.9 kWh (Galvin, 2022). EV adoption is projected to largely replace fossil-fuel vehicles in California by 2050, potentially reducing PM_{2.5} emissions by 50% (Wen et al., 2024). Under the EVs scenario (Fig. 8c), TEB-HW demonstrated consistently lower environmental impacts than those under the diesel scenario, with reductions exceeding 40% in FRS, FE, TE, TA, FPM, and GWP, and approximately 90% in HCT. Similar trends were observed for TEB-TCH and TCH-only (Figs. 8d, e), highlighting the environmental advantage of EVs. Notably, HCT decreased by > 80% in all zones, confirming that fuel-based transportation is a major contributor to human carcinogenic toxicity, primarily via PM_{2.5} and sulfur compound emissions.

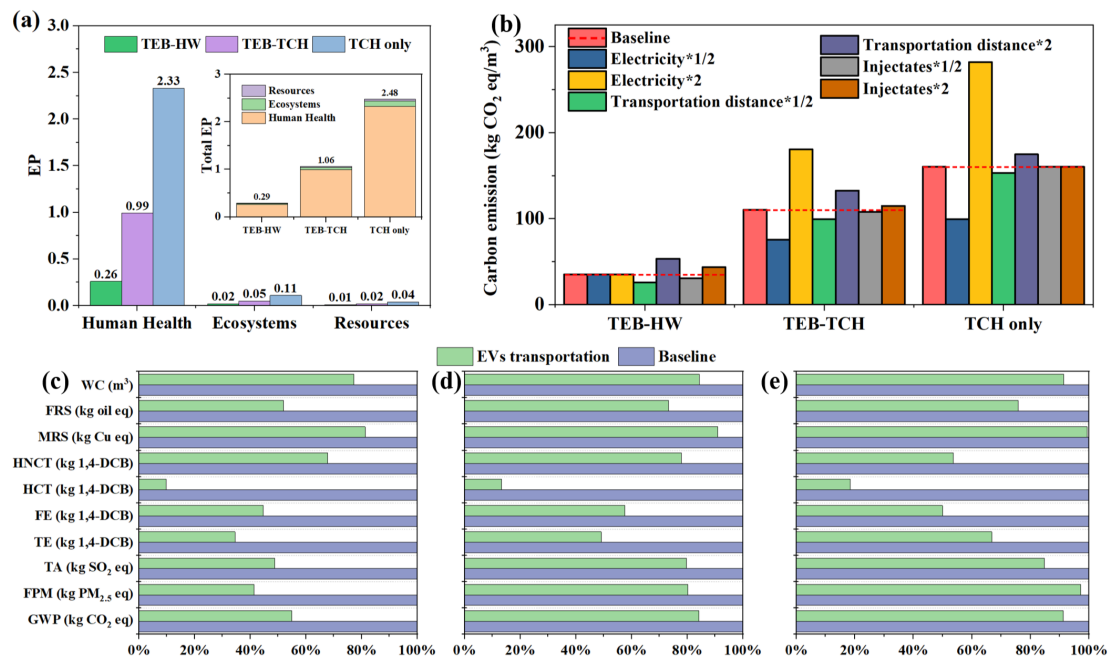


Fig. 8. (a) Overall endpoint results of TEB-HW, TEB-TCH and TCH only, (b) Carbon emissions under different sensitivity scenarios, (c, d, e) Sensitivity analysis under different transportation scenario for TEB-HW, TEB-TCH and TCH only. Note: The baseline scenario represents the scenario in which diesel vehicle transportation was used in the sustainability assessment of the current study.

3.2 Economic and social impacts

The economic and social sustainability results of TEB-HW, TEB-TCH and TCH only are shown in Fig. 9a with detailed data in Table 1. Five economic indicators, including direct project cost, project risk, remediation duration, land value and employment, were considered in the economic sustainability analysis. The average direct cost per cubic meter of remediated aquifer was \$14.3/m³ TEB-HW, significantly lower than TEB-TCH (\$31.7/m³) and TCH-only (\$51.4/m³), representing a cost reduction of 55% and 72%, respectively. This advantage is primarily due to TEB-HW's lower energy consumption and fewer required injection wells. Both TEB-HW and TEB-TCH exhibited marginally higher project risks compared with TCH-only due to potential uneven heating, which can delay remediation in heavily contaminated areas (Nemecek et al., 2018). In addition, daily temperature monitoring revealed rapid cooling at cold spots (e.g., TW-3 and TW-6), which were located farther away from the injection wells near the boundaries of study area (Fig. 4), potentially impairing efficiency. Yet, this can be mitigated via BMP optimization, such as increasing hot water injection wells and flow rates, and enhancing monitoring frequency.

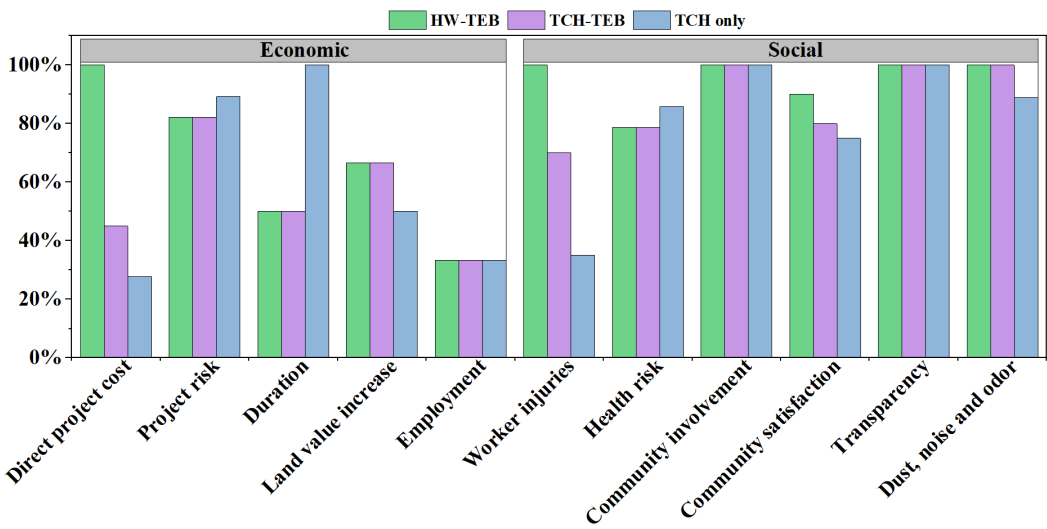
Remediation duration was 12 months for both TEB-HW and TEB-TCH, with bi-monthly post-heating monitoring to verify compliance. Optimized BMPs, such as increased injection frequency,

higher injectate concentrations, and timely replenishment, could further reduce remediation time and improve economic benefits. In contrast, TCH-only achieved cleanup in 6 months, demonstrating higher efficiency; however, its high-temperature treatment alters soil properties, potentially limiting post-remediation land reuse for green spaces and reducing land value compared to TEB-HW and TEB-TCH. All zones operated concurrently, maintaining equivalent local labor employment.

From the social sustainability aspect, worker safety, community health risk, community involvement and satisfaction, project transparency, dust, noise and odor emissions were considered. TEB-HW offered superior worker safety due to its simpler equipment design and the avoidance of high-temperature and electrical hazards, resulting in fewer reported injuries compared with TEB-TCH and TCH-only. Despite the implementation of safety training programs, hazardous conditions persisted on site for the latter two technologies, further highlighting this advantage of TEB-HW. On the other hand, both TEB-HW and TEB-TCH posed slightly higher community health risks than TCH-only due to injectate usage (See section 3.1.2), even when the injectates themselves are biodegradable (e.g., molasses, ethanol), consistent with observations reported by (Hou et al., 2016).

To reduce potential bias arising from subjective community perceptions, objective indicators were developed based on the implementation rate of 44 predefined BMPs, which quantitatively reflected community engagement, satisfaction, transparency, and noise control. All three remediation approaches demonstrated comparable performance in terms of community engagement and project transparency, characterized by proactive stakeholder communication during the design phase, regular progress updates and public meetings throughout implementation, and accessible feedback channels for community members and other stakeholders. Additional evaluation criteria are summarized in Table 1. Community satisfaction and dust, noise, and odor emission indicators were equivalent for TEB-HW and TEB-TCH, and consistently outperformed those of TCH only. In contrast, the extraction and wastewater/off-gas treatment processes associated with TCH only resulted in noticeable pollutant dispersion and elevated noise levels, as evidenced by on-site noise monitoring. These findings underscore that public acceptance is strongly influenced by direct, sensory impacts on daily life quality. Consequently, the broader environmental sustainability advantages of a remediation technology (e.g., lower carbon footprint) may be perceived as less relevant by local communities than the day-to-day operational nuisances experienced during

460 implementation (Hou et al., 2016).



461

462 **Fig. 9.** Comparison of economic and social impacts (Note: Higher values indicate greater sustainability)

Table 1 Numerical sustainability results for TEB-HW, TEB-TCH and TCH only

Indicator	Sub-indicator	Value			Unit	Score			Weight1	Score			Weight2	Final score		
		TEB-HW	TEB-TCH	TCH		TEB-HW	TEB-TCH	TCH		TEB-HW	TEB-TCH	TCH		TEB-HW	TEB-TCH	TCH
Environmental													0.33			
Resources	-	0.26	0.99	2.33	Ep	100	26.2	11.2	0.33	33.3	8.65	3.69		11.1	2.85	1.22
Ecosystem	-	0.02	0.05	0.11	Ep	100	40	18.2	0.33	33.3	13.2	6.01		11.1	4.36	1.98
Human health	-	0.01	0.02	0.04	Ep	100	50	25	0.33	33.3	16.5	8.25		11.1	5.45	2.72
Sum									1.00	100	38.35	17.9	0.33	33.3	12.66	5.92
Social													0.33			
Worker safety	Worker injuries	0.0007	0.001	0.002	Incide	100	70	35	0.16	16	11.2	5.6		5.28	3.69	1.85
	Health risk	3.93	3.93	4.29	/	78.6	78.6	85.8	0.16	12.57	12.57	13.7		4.15	4.15	4.53
Public acceptance	Community	5	5	5	/	100	100	100	0.16	16	16	16		5.28	5.28	5.28
	Community satisfaction	4.5	4	3.75	/	90	80	75	0.16	14.4	12.8	12		4.75	4.22	3.96
Impact to local	Transparency	5	5	5	/	100	100	100	0.16	16	16	16		5.28	5.28	5.28
.	Dust, noise and odor	5	5	4.44	/	100	100	88.8	0.16	16	16	14.2		5.28	5.28	4.69
Sum									1.00	90.97	84.57	77.5	0.33	30.02	27.91	25.59
Economic													0.33			
Cost	Direct project cost	24.6	54.7	88.7	\$	100	44.9	27.7	0.2	20	8.99	5.54		6.6	2.96	1.83
	Project risk	4.11	4.11	4.46	/	82.2	82.2	89.2	0.2	16.44	16.44	17.8		5.43	5.43	5.89
	Duration	12	12	6	Month	50	50	100	0.2	10	10	20		3.3	3.3	6.6
Benefit	Land value increase	3.33	3.33	2.5	/	66.6	66.6	50	0.2	13.32	13.32	10		4.39	4.39	3.3
	Employment	1.67	1.67	1.67	/	33.4	33.4	33.4	0.2	6.68	6.68	6.68		2.21	2.21	2.21
Sum									1.00	66.44	54.33	58.4	0.33	21.96	18.29	19.82
Sum													1.00	85.24	58.86	51.33

3.3 Overall sustainability

The normalized environmental, economic, and social sustainability impacts of the three remediation zones based on MCA are shown in Fig. 10a, with detailed calculation steps provided in Table 1. The TEB-HW zone demonstrated superior environmental sustainability performance, while also exhibiting markedly higher economic and social sustainability compared to both TEB-TCH and TCH only. The aggregated sustainability results (Fig. 10b) were 85, 59, and 51 for TEB-HW, TEB-TCH, and TCH only, respectively, confirming that TEB-HW achieved the highest overall sustainability performance in remediation processes, whereas the TCH-only zone represented the least sustainable option among the evaluated alternatives.

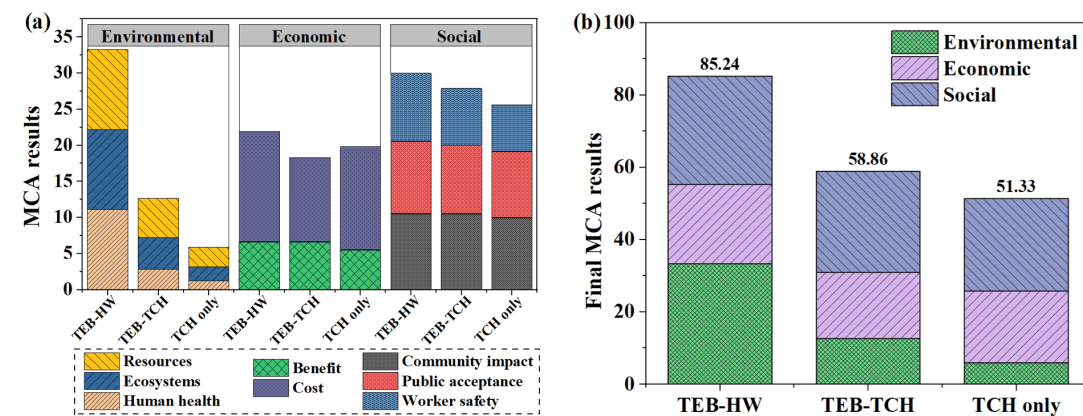


Fig. 10. Sustainability assessment results: (a) MCA results of each indicator, (b) Final MCA results of overall results

3.4 Implications and limitations

3.4.1 Potential strategies for BMPs optimization to improve sustainability

A comparison of ISTEb with other bioremediation and TCH technologies reported in previous studies was conducted and presented in Table 2. The carbon emission per cubic meter of soil and groundwater in ISTEb were approximately three times (54.7 kg vs. 23.5 kg) of the average emission from standalone biostimulation or bioaugmentation, while reducing costs by approximately 70% (from \$51.5 in average to \$23). When compared to conventional TCH, ISTEb demonstrated an 80% (54.7 kg vs. 270 kg) reduction in carbon emissions and a 91% (from \$267 in average to \$23) decrease in costs. These findings highlighted the advantage of ISTEb in achieving remediation targets without substantially increasing carbon emissions while achieving significant cost reductions. Furthermore, the optimization of BMPs in key ISTEb processes can further enhance its

sustainability potential. For instance, the integration of solar energy into subsurface heating can yield notable environmental, economic, and social benefits. At a chemical production facility in the Czech Republic, the application of a hybrid solar-electric system for groundwater extraction, heating, and reinjection successfully elevated subsurface temperatures to 40°C and significantly accelerated bioremediation process (Nemecek et al., 2018). The Drake Landing Solar Community in North America, as the first regional-scale solar thermal exchange system, demonstrated the potential of solar energy application in TEB of contaminated sites (McCartney., 2016). This integration of renewable energy sources exemplifies the strategic role of technology in decoupling economic growth from environmental degradation, a fundamental principle of the circular economy promoted by SDG 12 (Karpe et al., 2025).

Transportation, primarily involving the delivery of construction materials and injectates, was identified one of the key environmental impact factors in TEB-HW and TEB-TCH implementation (Figs. 6a and 6b). Relevant BMPs were incorporated into the sustainability assessment framework, including localized material procurement to minimize transport distances and optimized well/pipeline layouts to reduce material transport quantities. These measures directly support SDG 12.7 (Promote public procurement practices that are sustainable, in accordance with national policies and priorities) by promoting sustainable public procurement practices that minimize the material footprint embedded in the remediation supply chain (Adjei-Bamfo et al., 2019). The emissions from transportation exhibited positive correlations with both transport distance and load mass, underscoring the critical importance of optimized remediation design and operations (Glensor and Muñoz, 2019). Sensitivity analysis demonstrated that EVs offered significantly greater carbon reduction benefits compared to diesel-powered transportation, achieving carbon emission reductions of approximately 45% and 20% for TEB-HW and TEB-TCH, respectively. China's Ministry of Transport has pledged to achieve large-scale deployment of EVs by 2028, targeting substantial carbon emission reductions in the transportation sector (CMT, 2024). While EVs do not directly generate emissions during transportation, their carbon footprint can be traced back in the upstream to electricity generation processes. Consequently, the carbon intensity of EVs transportation depends on regional energy portfolios. Under the same transportation scenarios, the carbon emission intensity of EVs in China was 20% higher than that in the European Union (Xia et

al., 2022), as China's electricity supply was predominantly (70%) derived from coal-fired power generation (Ding et al., 2022). This life-cycle perspective reinforces the SDG 12 mandate for a holistic approach to consumption, where technological shifts (e.g., EVs) must be matched with cleaner energy production to truly close the loop on carbon efficiency (He et al., 2025).

On the other hand, electricity consumption for heating was the primary source of environmental and cost impacts for TEB-TCH, whereas it exerts negligible influence on TEB-HW since natural gas was used for heating water. For energy-intensive remediation technologies, advancing sustainable energy infrastructure represents a critical pathway for achieving carbon mitigation targets. However, despite the lower overall sustainability of TEB-TCH compared to TEB-HW, it retained broad applicability. For instance, in contaminated sites characterized by low permeability and limited hydraulic conductivity, TEB-TCH can achieve better heating efficiency and achieve a more uniform temperature distribution (Kaur et al., 2021). In the context of SDG 12, this highlights the necessity of precision in technology application to ensure that resource-intensive methods are only employed where strictly necessary to avoid the wasteful consumption of energy capital. Consequently, selecting the appropriate remediation technology based on specific subsurface formation characteristics was essential (O'Connor et al., 2019). The BMPs proposed in this study specifically emphasized the critical importance of preliminary site characterization and the subsequent selection of a compatible remediation technology. For instance, during the design phase, it is critical to conduct thorough investigations of potential contaminants and their concentrations. Both TEB-HW and TEB-TCH are suitable for remediating low to medium concentrations of organic contaminants, but are not recommended for sites with high contaminant concentrations or heavy metal pollution.

The utilization of injectates was identified as another critical factor significantly influencing the sustainability of TEB-HW and TEB-TCH. For TEB-HW, magnesium sulfate application accounted for 24% of upstream carbon emissions and contributed to over 60% of human toxicity impacts. For TEB-TCH, although electricity consumption reduced magnesium sulfate's contribution to overall carbon emissions, its impact on human toxicity and ecotoxicity remained above 20%. Similarly, Ni et al. reported that molasses exhibited the second-highest environmental impact, demonstrating ecotoxicity due to the use of fertilizers, pesticides, and energy during its upstream production (Ni et

al., 2020). However, studies indicated that ethanol, a green injectate, emerged as an environmentally favorable energy source because its upstream production cycle demonstrated significantly lower energy consumption than conventional fossil fuels while maintaining non-toxic contributions for human health (Feng et al., 2010). The shift towards such green injectates resonates with SDG 12.4, which aims for the environmentally sound management of chemicals throughout their life cycle, by replacing toxic inputs with bio-based, lower-impact alternatives (Berthiaume, 2023). This necessitated explicit consideration of injectate-induced sustainability impacts during TEB-HW and TEB-TCH implementation.

The BMPs proposed in this study incorporated specific evaluation criteria for injectate application to minimize their impacts on the overall sustainability, including (1) a comparative assessment of remediation efficacy, environmental footprint, and economic costs among different injectates during the design phase, with priority given to green injectates characterized by high treatment efficiency, low costs and environmental burdens, and (2) the implementation of optimized dosing protocols to eliminate excessive injectates input during remediation operations. These protocols emphasize the strategic role played by technologies in facilitating an efficient circular model, ensuring that every unit of resource input translates effectively into remediation outcomes without generating unnecessary waste. From a forward-looking perspective, innovative approaches such as the patent-based prospective LCA method proposed by Spreafico, 2025 offer valuable tools for identifying emerging innovations-such as novel green injectates-that could potentially reshape the environmental and economic profile of ISTEb. Integrating such prospective assessments with the BMP framework would enhance its capacity to guide long-term technological innovation and strategic decision-making toward more sustainable remediation pathways.

3.4.2 Perspective for global carbon reduction in soil and groundwater remediation

Globally, over 5 million contaminated sites exist, with remediation generating billions of tons of carbon emissions annually (Hou et al., 2023). ISTEb provides a pathway for green and sustainable remediation in both developed and developing countries. However, its adaptability varies significantly across geographic and socio-economic contexts. In developed countries, bioremediation adoption has increased from ~11% in 2000 to ~25% in 2023, while conventional approaches, mainly ex situ pump-and-treat (31%), *in situ* chemical oxidation (16%), and ISTT (9%),

still dominate (EPA, 2023). This trend highlights the potential to expand ISTEb to improve environmental and carbon performance. In developing countries, *ex situ* methods are also preferred due to urgent land redevelopment needs, shorter remediation timelines, and simpler regulatory processes (Kovalick and Montgomery, 2017). In China, cement kiln co-processing (37%) and excavation/landfill (14%) dominate, while bioremediation accounts for less than 1% (Ma et al., 2018, Meng et al., 2025). This heavy reliance on resource-intensive remediation approaches contrasts sharply with the principles of SDG 12.5, which advocates for substantial waste reduction through prevention, reduction, recycling, and reuse (Dam et al., 2025). Although ISTEb offers clear advantages in energy efficiency and carbon reduction under such contexts, its adoption faces distinct socio-economic barriers, including limited local expertise, insufficient financing mechanisms, and the declining demand for brownfield redevelopment similar to the recent trends observed in China's recent real estate sector.

Furthermore, the sustainability advantages of ISTEb identified in this study were most pronounced in regions with well-established regulatory frameworks. For example, the superior environmental performance of TEB-HW becomes economically compelling in jurisdictions that incentivize low-carbon technologies through fiscal policies or emissions trading systems. Conversely, in regulatory environments where remediation decisions are driven primarily by cost and fast remediation in many developing regions, the long-term sustainability benefits of ISTEb are undervalued, resulting in a persistent market advantage for conventional excavation-based technologies. This regulatory-technology misalignment substantially impedes the adoption of innovative and sustainable remediation technologies despite their demonstrated technical and environmental advantages (Hou et al., 2016). This highlights a significant gap in achieving SDG 12, as the absence of supportive policy frameworks hinders the application of technologies capable of integrating soil remediation with environmental health. Therefore, unlocking the full potential of ISTEb requires parallel advancements in policy frameworks that explicitly reward sustainable performance metrics. Overall, this study offers valuable insights for governments and remediation practitioners worldwide and offers a reference point to support the strategic advancement and adoption of ISTEb.

3.4.3 Limitations

Although the developed framework demonstrated that ISTEb technologies exhibit relatively high

sustainability and low carbon emissions from energy and material consumption, variations in hydrogeological conditions, contaminant types, and contamination levels across different sites may lead to different sustainability outcomes. The lack of additional validation at comparable sites may limit the generalizability of the findings in the current study. Furthermore, it is important to note that additional emissions arise from microbial activities in the bioremediation process, which were not considered in this study due to the lack of quantitative field estimates. Incorporating these metabolic emissions in the sustainability framework and the total carbon footprint of ISTEb is recommended to achieve a more accurate and comprehensive assessment of its environmental impacts. Such improvement would deepen the understanding of the sustainability of ISTEb and further support the development of optimized, carbon-neutral remediation strategies.

Table 2 Carbon emission and cost for TCH, bioremediation and ISTEb

Technology	Location	Contaminant	Carbon emission (kg/m³)	Cost (\$/m³)	Reference	
TEB-HW	Qingyang, China	PHCs	35.1	14.3	This study	
TEB-TCH			74.4	31.7		
Average carbon emissions of bioremediation:			Average cost of bioremediation:			
54.7kg/m³			\$23			
Bioremediation	Shanghai, China	CAHs	25.1	/	Ni et al., 2020	
	/	CAHs	22.1	/	Harclerode et al., 2016	
	Glasgow, England	PHCs	23.3	/	Sampson et al., 2013	
	/	PHCs	/	64	Kujat, 1999	
	/	PHCs	/	47	EPA, 2010	
	East Vandenberg AFB, CA, USA	CAHs	/	52	EPA, 2010	
	Dallas, TX, USA	CAHs	/	43		
	Average carbon emissions of bioremediation:			Average cost of bioremediation:		
	23.5kg/m³			\$ 51.5		
	TCH	Tianjin	CAHs	280	267	Yang et al., 2023
/		/	212	/	Amponsah et al., 2018	
/		/	320	/	Meng et al., 2025	
Average carbon emissions of TCH:			Average cost of bioremediation:			
270kg/m³			\$ 267			

4 Conclusions

This study developed a novel, fully quantitative sustainability assessment framework integrating LCA and BMPs to evaluate ISTEBS, including TEB-HW and TEB-TCH. The results demonstrated that TEB-HW and TEB-TCH significantly outperformed conventional TCH in terms of environmental, economic and social sustainability. Specifically, TEB-HW and TEB-CH reduced carbon emissions by 78% and 31%, respectively, and achieved cost savings of 72% and 38%, and resulting in higher community satisfaction. Normalized multi-criteria analysis confirmed that ISTEBS technologies attained high composite sustainability scores, highlighting their advantage as low-carbon, cost-effective, and socially acceptable remediation strategies. This work extends the sustainability assessment of ISTEBS beyond conventional efficiency metrics by quantifying environmental, economic, and social impacts across the full life cycle, offering actionable strategies to enhance sustainability performance.

Sustainable remediation is not only a technical challenge, but more importantly, a regulatory and behavioral issue that directly aligns with the principles of SDG 12. Decisions made by practitioners at every stage of the remediation process ultimately determine the sustainability performance of a project, effectively shaping how well the remediation industry can contribute to SDG 12's targets. Based on the findings of this study, several recommendations are proposed for policymakers and practitioners. For policymakers, establishing appropriate quantitative calculation methods and tools, such as the LCA-BMPs model developed in this work, is essential for strengthening practitioners' understanding of sustainable remediation. Such tools can reinforce both private and public benefits, thereby accelerating market adoption of ISTEBS technologies in line with SDG 12. For practitioners, adopting a site-specific technology selection protocol is critical. TEB-HW performs particularly well for aquifers with relatively high permeability, where hot water injection enables rapid subsurface heating, whereas TEB-TCH is better suited for low-permeability formations, where thermal conduction provides more uniform heating.

Although both ISTEBS approaches typically require longer remediation durations than TCH-only system, their substantial reductions in energy consumption, material use, and social risks outweigh this limitation, especially when integrated with optimized BMPs such as green injectates, renewable energy, and localized material procurement. Future research should incorporate *in situ* microbial

646 processes (e.g., anaerobic fermentation) into sustainability assessment frameworks, to better
647 quantify their contributions to carbon emissions and further refine holistic sustainability evaluations,
648 thereby advancing the scientific basis for sustainable remediation practices in compliance with SDG
649 12.

Authorship contribution statement

Zongshuai Yang: Conceptualization, Investigation, Methodology, Visualization, Writing-original draft. Qing Wang: Investigation, Methodology, Visualization. Changlong Wei: Methodology, Visualization. Zhuanxia Zhang: Investigation. Zhiwen Tang: Investigation. Yanxi Li: Resources, Investigation. Gubai Luo: Investigation. Frederic Coulon: Writing-review & editing. Liwu Fan: Resources, Investigation. Xin Song: Resources, Conceptualization, Methodology, Supervision, Writing-review & editing.

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