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Integrated resiliency and sustainability assessment of contaminated site remediation: Case study

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ABSTRACT: Several technologies have been developed to remediate contaminated sites; however, there is an increasing emphasis on integrating sustainability across environmental, social, and economic dimensions into remediation practices. Furthermore, it is essential to ensure that remediation activities are resilient to external stressors, including the adverse impacts of climate change, throughout their lifecycle. In this regard, a comprehensive assessment of various technologies is necessary to incorporate these aspects into the remediation design and implementation. This study employs the Tiered Quantitative Life Cycle Sustainability and Resiliency (TQUALICSR) framework to comprehensively assess remediation of a contaminated site at an oil refinery facility in Lincoln, Nebraska, USA. The site was contaminated with toxic organic compounds (e.g., carbon tetrachloride, chloroform, dibromoethane) in the soils near the ground surface, and the contamination plume extended to groundwater deep underneath. After conducting a detailed site characterization, risk assessment, and technical screening of remediation technologies, three methods, specifically excavation and disposal (ED), electrokinetic remediation (EKR), and emulsified zero-valent iron treatment (EZVI), were selected to be evaluated for soil remediation. Two viable options, specifically pump-and-treat (P&T) and EZVI, were selected for evaluation in groundwater remediation. In this study, these technologies were assessed for their resilience to climate change impacts, revealing ED for soil remediation and EZVI for groundwater remediation as the most resilient methods. Furthermore, the sustainability assessment of these different technologies exhibited varying levels of long-term impacts across the three dimensions of sustainability. The indicators quantified during the resilience and sustainability assessments were integrated to develop a Resilient Sustainability Index (RSI), which can inform final decision-making. Overall, the results showed that, for soil remediation, ED (RSI = 0.46) is the least preferred option, whereas EKR (RSI = 0.51) and EZVI (RSI = 0.77) demonstrate greater viability, despite the higher resilience of ED. For groundwater remediation, EZVI (RSI = 0.79) significantly outperformed PT (RSI = 0.28) in both resilience and sustainability.

KEYWORDS: Soil pollution, groundwater pollution, site remediation, resiliency, sustainability.

1 INTRODUCTION

Contaminated sites pose a significant risk to human health and the environment. Risk-based remediation is typically employed to remediate contaminated sites, where the risk of contamination to human health and the environment is characterized, and remedial goals are established to address these risks (Sharma & Reddy 2004; USEPA, 2001). Moreover, CERCLA's (Comprehensive Environmental Response, Compensation, and Liability Act) nine criteria guide remediation method selection based on effectiveness, compliance, cost, and state and community acceptance (USEPA, 1980). However, these approaches do not account for the broader sustainability implications of remedial action (e.g., carbon footprint). Agencies worldwide have been striving to incorporate sustainability principles, including environmental impacts, social acceptance, and economic considerations (Reddy & Adams 2015). Furthermore, the remediation method adopted must be resilient to any external stressors, such as climate change, including sea level rise, hurricanes, wildfires, extreme flooding, and drought, that could impact its performance throughout its design life. In this regard, a resiliency assessment that considers the potential stressors from climate impacts at the remediation site is imperative. Additionally, long-term sustainability impacts of remediation methods must be quantified to understand the environmental, social, and economic benefits of adopting a specific remedial method compared to other alternatives (Reddy et al. 2024a).

This study employs a comprehensive quantitative assessment to select a remediation method for cleaning up contaminated soils and groundwater at a soybean oil refinery facility in Lincoln, Nebraska, USA. Different remedial alternatives were selected for soils and groundwater remediation following site characterization and risk assessment. The Tiered Quantitative Life Cycle Sustainability and Resiliency (TQUALICSR) framework, developed by Reddy et al. (2024b), was employed to assess the selected remedial methods to identify the most resilient and sustainable alternative. The resiliency assessment involved evaluating the vulnerability of the remediation methods against potential extreme weather events at the site. Further, the long-term environmental sustainability impacts of application of these methods were assessed through life cycle assessment, the social sustainability was evaluated based on a questionnaire focusing on different impacts the remediation method could have on the community and stakeholders, and the economic sustainability was assessed by assessing the economic costs and benefits of employing each method. Finally, an integrated resilient sustainability index (RSI) was calculated to demonstrate the applicability of the framework in selected resilient and sustainable methods for contaminated site remediation.

2 CONTAMINATED SITE CASE STUDY

The site considered for assessment is a soybean extraction processing and oil refining facility, owned by Archer Daniels Midland (ADM), located in Lincoln, Nebraska, USA. In 2008, carbon tetrachloride contamination was discovered in nearby wells, prompting an investigation into potential contamination at the facility. The investigation revealed that the contaminants were found in soil near the bean silos and in a groundwater contaminant plume that extends up to 0.75 miles northeast of the refinery. The contaminants found included carbon tetrachloride, carbon disulfide, chloroform, methylene chloride, and 1,2-dibromoethane. These contaminants were found in both soil and groundwater, necessitating site cleanup. Furthermore, the contamination was discovered to have resulted from an accidental petroleum release from broken underground pipes in 1999, as well as from the continuous release of carbon tetrachloride, which had been used as a fumigant, prior to ADM's acquisition of the facility.

Numerous remediation technologies have been developed for the cleanup of contaminated soil and groundwater, including monitored natural attenuation, excavation and disposal, air sparging, electrokinetic remediation, soil flushing, bioremediation, soil vapor extraction, and the emulsified zero-valent iron method. These remediation methods were screened using the Technology Screening Matrix (FRTR, 2020), developed by the Federal Remediation Technologies Roundtable, based on the USEPA-CERCLA nine-point criteria. Following the technical screening, excavation and disposal (ED), electrokinetic remediation (EKR), and emulsified zero-valent iron (EZVI) were selected as the potential soil remediation methods. Pump and Treat (PT) and EZVI were chosen as potential groundwater remediation methods for further evaluation.

ED is a commonly used method in environmental cleanup that involves physically removing contaminated soil and its disposal. However, the method could be infeasible based on the site and the extent of contamination (USEPA, 2001). Meanwhile, EKR is an in-situ technique, where electricity is propagated into the soil through vertical wells with electrolytes. The electrical field promotes the mobility of contaminants towards electrodes for subsequent removal. Furthermore, the heat generated by the electric current in the soil can volatilize volatile organic compounds (VOCs), which comprise the majority of the contaminants at the site (Paramitadevi et al., 2022; Heron et al., 1998). On the other hand, EZVI uses food-grade vegetable oil, a surfactant, elemental iron, and water, and combines them to form an emulsified mixture. This mixture is directly injected into the subsurface and can interact with dense non-aqueous phase liquids (DNAPLs) through abiotic and biotic processes. The oil facilitates long-term biodegradation, requires minimal labor during the operational period, and can be used to treat both contaminated soils and groundwater (Quinn et al. 2005). Finally, PT is a commonly used remediation method for cleaning up contaminated groundwater. The method involves pumping groundwater using wells to an above-ground treatment system, where contaminants can be removed (MacKay & Cherry 1989). VOCs can be easily removed from their dissolved state through aeration, which can be achieved using a tray air stripper. The remedial designs of these alternatives aimed to reduce contaminant concentrations, thereby minimizing human exposure risk.

3 RESILIENCY AND SUSTAINABILITY ASSESSMENT

The selected remediation alternatives were compared based on their resilience to extreme weather events and their sustainability across environmental, social, and economic dimensions. The Tiered Quantitative Life Cycle Sustainability and Resiliency (TQUALICSR) framework, developed by Reddy et al. (2024b), facilitates the quantification of resiliency and sustainability, enabling comparisons for selecting the most resilient and sustainable alternatives. The general framework of the methodology is presented in Figure 1. According to the framework, assessment begins by defining the project's goal and scope, and designing alternatives based on stakeholder preferences, followed by a resiliency assessment. Alternatives that meet the resiliency conditions are carried forward to the sustainability assessment, while those that do not are modified to achieve the required resiliency. The sustainability assessment is then conducted on the resilient alternatives, followed by the integration of resiliency and sustainability metrics. Alternatives that fail to meet sustainability requirements are further refined, while those that satisfy the requirements are considered resilient and sustainable. The methodology adopted, based on the framework, is described in the subsequent sections.

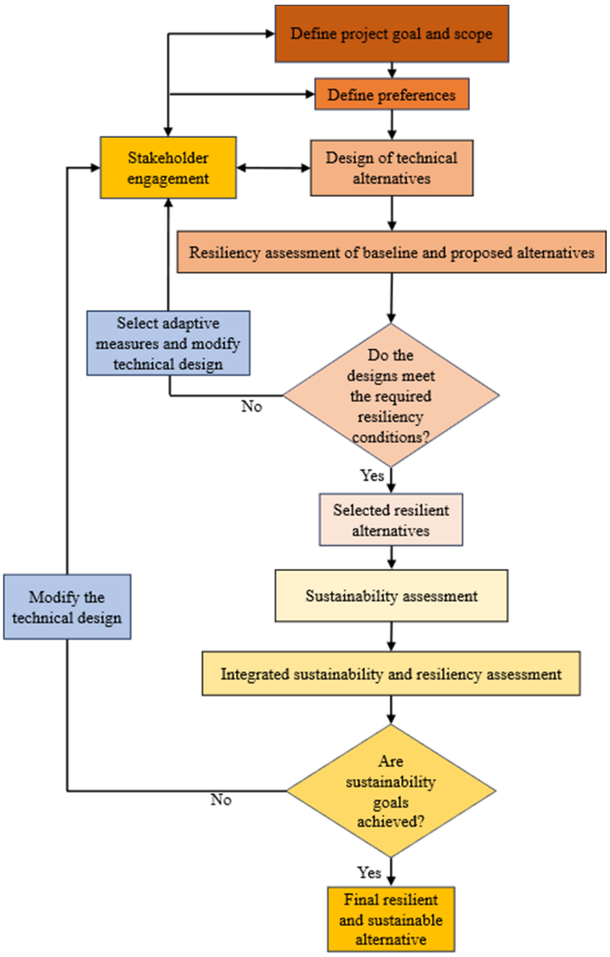

Figure 1. Integrated resiliency and sustainability assessment framework (from: Reddy et al. 2024b)

3.1 *Resiliency assessment*

The TQUALICSR framework outlines a detailed procedure to incorporate different dimensions of resiliency. To begin with, resiliency is categorized into requirements, criteria, and indicators. The requirements include technical resiliency and cascading environmental, social, and economic consequences of a resilient or non-resilient design. Further, these requirements are categorized into specific criteria, which are further associated with different indicators. Resiliency is quantified using the selected indicators, and the indicator values are integrated to get an overall resilience index (RI).

Indicators were rated on a relative scale from 0 to 4 (0 - extreme negative impact and 4 - low negative impact), based on potential performance deterioration under external stressors, the system's capacity to recover, and the consequent environmental, social, and economic implications in the event of failure. Different tools, including Climate Check, the Federal Emergency Management Agency (FEMA), the Climate Risk and Resiliency Portal (ClimaRR), and Climate Mapping for Resilience and Adaptation (CMRA), were utilized to identify potential climate impacts at the site. Flooding, frost days, ice storms, tornadoes, and droughts were considered stressors that could affect the remediation methods during their design life. The alternatives were assessed against each disaster event to quantify their resiliency. Further, the scores are integrated to obtain each alternative's Resiliency Index (RI). The methods for integrating the scores are described in the subsequent section.

3.2 *Integrated resiliency and sustainability assessment*

Following the resiliency assessment, an integrated sustainability assessment is conducted based on the requirements that cover the environmental, social, and economic dimensions of sustainability, which are divided into different criteria and ultimately into indicators. To integrate resiliency and sustainability, the resiliency of alternatives was considered a criterion under each sustainability requirement.

A quantitative environmental sustainability analysis of the remediation alternatives was conducted using life cycle assessment (LCA) with SimaPro (Version 9.0). SimaPro is a widely used tool to perform LCA of various engineering projects. It incorporates multiple impact assessment methodologies and databases tailored to different regions worldwide. The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), developed for the US, was used in this study. The USEPA (United States Environmental Protection Agency) developed the TRACI to assess environmental impacts using characterization factors applicable for locations across the US. The impact indicators include global warming, acidification potential, eutrophication potential, respiratory effects, carcinogenic and noncarcinogenic emissions, ozone layer depletion potential, ecotoxicity, smog, and fossil fuel depletion.

Furthermore, SiteWise, a Microsoft Excel-based tool developed to quantify the energy requirements, emissions, and other metrics associated with remediation projects, was used to quantify additional indicators. The tool quantifies indicators similar to those of SimPro, such as greenhouse gas emissions (global warming potential), SO_x emissions (acidification potential), NO_x emissions (eutrophication potential), and PM_{10} emissions (respiratory effects). Additional indicators include total energy consumption, electricity usage, water usage, and risk of accidental fatality and injury.

The factors to consider in assessing the social sustainability of the remediation method include the impact on public health, well-being of the community, and impact on the standard of living around the contaminated remediation sites. The social sustainability assessment is structured to evaluate the effects of a remediation technology on socio-individual, socio-community, socio-economic, and socio-environmental criteria (Reddy et al., 2014). To facilitate this evaluation, a questionnaire was developed based on the Social Sustainability Evaluation Matrix (Reddy et al. 2014), incorporating the abovementioned criteria. Researchers completed the questionnaire from the perspective of stakeholders, and the results were used to assess the social sustainability of the remediation alternatives.

The economic aspects were divided into direct and indirect costs, as well as direct and indirect benefits. Direct costs were quantified based on estimates for design, equipment, operation, maintenance, and disposal for each alternative. Further, the indirect costs and direct and indirect benefits were quantified by identifying indicators representing the criteria and rating them on a scale of 0 to 4 (0 - extreme negative impact; 4 - low negative impact).

The indicator values from the environmental, economic, and social sustainability assessments were then normalized using a value function that ranged from 0 to 1, allowing for direct comparison of alternatives and integration of indicator values from different units and metrics. Based on the trends of the indicator value (decreasing or increasing sustainability with increasing values), the curve shape (convex, concave, linear, or S-shape), and maximum and minimum values (values that represent highest and lowest possible sustainability scenarios for an indicator), the normalized indicator value can be obtained using equations (1) and (2), as follows (Reddy et al. 2024b):

$$V_i = \left[B \times \left[1 - e^{-K_i \times \left(\frac{|S - S_{min}|}{C_i} \right)^{P_i}} \right] \right] \tag{1}$$

$$B = \left[\frac{1}{1 - e^{-K_i \times \left(\frac{|S_{max} - S_{min}|}{C_i} \right)^{P_i}}} \right] \tag{2}$$

Where V_i represents the normalized indicator value, the B factor maintains the values of V_i between 0 and 1; S is the quantified indicator value; P_i is the shape factor, which determines the shape of the indicator value curve. A P_i value of 1 is used for a linear function, less than 1 for concave, and a value greater than 1 for convex or S-shaped functions. The values of C_i and K_i determine the inflection points of the curve on the x-axis and y-axis, respectively. These parameters can be customized for different indicator types.

The normalized indicator values were then integrated as weighted summations to obtain the final resilient sustainability index (RSI). The weights can be manually assigned based on the quality of the data obtained in the analysis, expert judgment, and stakeholder preferences. Several other multicriteria decision analysis tools, as detailed in Reddy et al. (2024b), can be employed to weigh and integrate the indicators. This study employed a multicriteria decision analysis tool called MIVES (Integrated Value Model for Sustainability Assessment) to integrate these indicator values, assigning equal weights to each indicator within a criterion, each criterion within a requirement, and ultimately to each requirement (Boix-Cots et al., 2022). The weighted sum of the normalized indicator values gives the value of a criterion. Similarly, the weighted sum of the criteria values yields requirement values, and finally, the weighted sum of the requirement values provides the comprehensive RSI. The RSI values can help decision-making when selecting the most resilient and sustainable alternative.

4 RESULTS AND DISCUSSION

4.1 *Resiliency assessment*

The resiliency indicators were rated and integrated to determine the resiliency of alternatives against chosen stressors- flooding, frost days and ice storms, tornadoes, and droughts. The RIs for each remediation alternative are presented in Figure 2. The representative set of indicators used to assess resiliency against flooding for groundwater remediation is presented in Table 1. A similar assessment was conducted to determine the RI for each alternative against all the considered stressors.

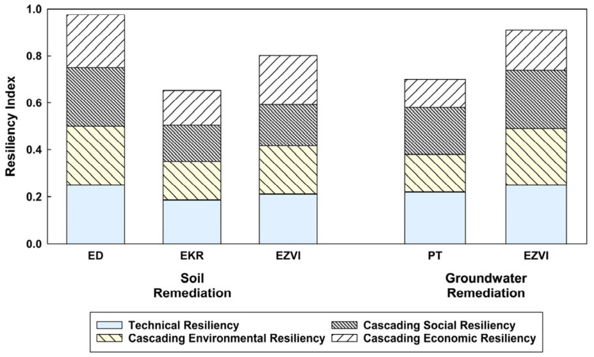

Figure 2. Resiliency indices for soil remediation using ED (excavation and disposal), EKR (electrokinetic remediation), and EZVI (emulsified-zero valent iron), and groundwater remediation using PT (pump and treat) and EZVI.

Table 1. Resiliency indicators and rating for groundwater remediation against flooding.

Requirement	Criteria	Indicator	Rating	
			PT	EZVI
Technical resiliency	Performance deterioration	Treatment performance	1	3
		Residual contaminant spread	3	2
	Time for deterioration	Performance loss	2	2
		Contaminant dispersion	2	3
	Time in deteriorated state	Impact on the remediation process	2	2
	Performance recovery	Remediation efficiency after redesign	2	3
	Time for recovery	Time for a redesign	1	2
Cascading environmental resiliency	Air	Release of VOCs	4	4
	Water	Contaminants are spreading to wells and creeks	1	2
		Contaminant migration to shallow zones	1	2
	Human health	Exposure to workers	3	4
		Exposure to the public	1	2
	Land	Contamination of topsoil	3	3
Cascading social resiliency	Socio-individual	Worker exposure risk	2	3
		Job impact	3	3
	Socio-community	Impact on local residents	1	1
		Impact on agricultural fields	2	3
		Community trust in refinery	1	3
	Socio-environment	Air quality degradation from VOCs	4	4
		Water quality degradation from damage	1	1
	Socio-economic	Effect on local businesses	2	3
		Agricultural yield impact	3	3
Cascading economic resiliency	Indirect benefits	Redesign cost	3	4
		Increased maintenance cost	2	4
	Indirect benefits	Decrease in property values	3	3
		Refinery business impact	3	3
	Indirect benefits	Employment during redesign	2	1
	Indirect benefits	Improved water management	4	4
		Improved soil quality	4	4

In soil remediation, ED was found to be the most resilient alternative, with an RI score of 0.98, compared to 0.80 for EZVI and 0.65 for EKR. ED does not pose any future threat due to external stressors, as it involves the removal of all the contaminated soil. This is highlighted in technical resiliency and cascading environmental and social resiliencies, with a score of 0.25 each. However, ED had an economic resiliency of 0.23, as other alternatives provide potential employment opportunities during maintenance and redesign in case of failure. Furthermore, EZVI performs better than the EKR, as the EKR involves above-ground structures that can be affected by external stressors, such as floods and ice storms. Meanwhile, EZVI (RI = 0.94) was more resilient in groundwater remediation than PT (RI = 0.72). PT involves equipment and above-ground structures that are prone to damage due to stressors and disruptions. These results affirm the resilience of remedial alternatives under stressors resulting from changing conditions and extreme weather events.

4.2 *Environmental sustainability assessment*

The input materials used for the SimaPro and SiteWise analysis are listed in Table 2. The materials required were assumed to be transported to the site from Lincoln City, 20 Km from the facility. However, zero-valent iron for EZVI remediation was considered to be obtained from a facility in Chicago and transported by rail. The normalized environmental impacts from SimaPro comparing the alternatives are presented in Figure 3(a) for the soil remediation and Figure 3(b) for groundwater remediation, and the same for SiteWise analyses are presented in Figure 4.

Table 2. Materials inventory for environmental sustainability assessment.

Materials	Soil Remediation			Groundwater Remediation	
	ED	EKR	EZVI	PT	EZVI
Excavating soil (m^3)	9908.5	509.40	-	-	-
PVC (Metric ton)	10.63	0.12	-	1.17	-
Backfill sand (m^3)	9908.5	509.40	-	-	-
EDTA (kg)	-	410.5	-	-	-
NaOH (kg)	-	1132.0	-	-	-
Steel electrodes (Metric ton)	-	7.44	-	-	-
Zero valent iron (Metric ton)	-	-	19.89	-	15.95
Vegetable oil (Metric ton)	-	-	8.95	-	7.18
Steel sheets-Tray air stripper (kg)	-	-	-	272	-

Results from the SimaPro analysis indicate that EZVI had lower environmental impacts than ED and EKR in soil remediation, as well as lower impacts than PT in groundwater remediation. Specifically, EZVI involves lower energy usage, minimal soil disturbance, and limited use of heavy machinery compared to the other two methods, significantly reducing its impacts in several categories. Meanwhile, ED involves significant mechanical excavation and transport; thus, the results reflect the same. Further, excavation required for well setup, disposal of the excavated soil, and considerable energy demands contribute to the impacts associated with EKR. Similarly, in groundwater remediation, PT showed significantly higher impacts across all categories when compared to EZVI. This is primarily due to the longer operation phase and material requirements.

Similarly, SiteWise results indicate that EZVI had lower environmental impacts across various impact categories for both soil and groundwater. However, the accidental risks were higher than those in EKR for soil remediation and in PT for groundwater remediation. These results underscore the importance of considering environmental impacts as a criterion in decision-making, as significant variability can arise from the method used to achieve the same remediation goals. EZVI demonstrates consistently lower impacts across all environmental impact categories for both soil and groundwater remediation, making it a more suitable option for prioritizing environmental sustainability.

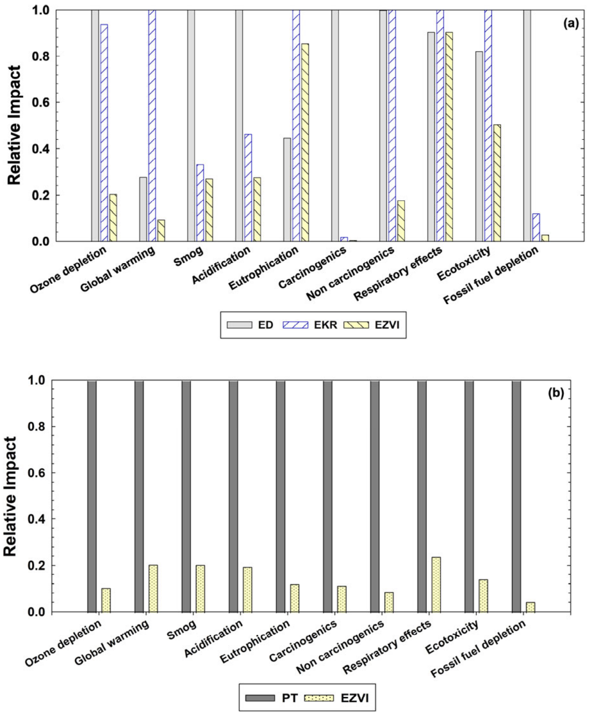

Figure 3. SimaPro environmental impacts for (a) soil remediation using ED (excavation and disposal), EKR (electrokinetic remediation), and EZVI (emulsified-zero valent iron), (b) groundwater remediation using PT (pump and treat), and EZVI.

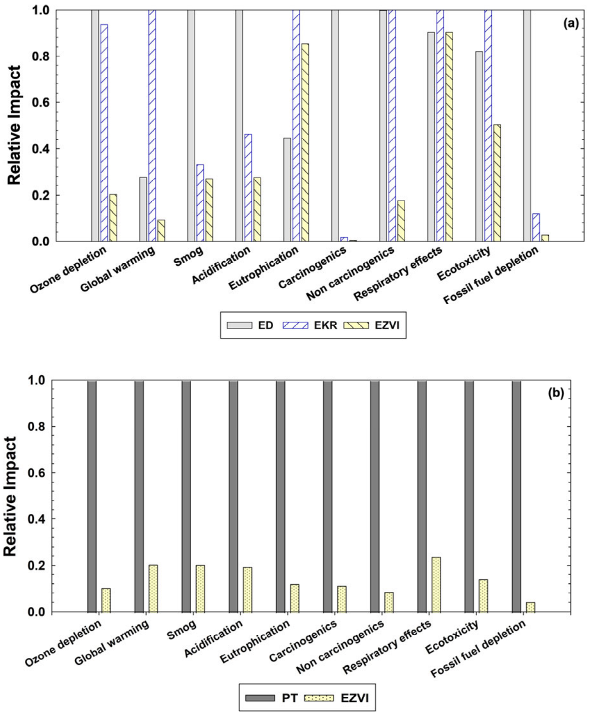

Figure 4. SiteWise environmental impacts for (a) soil remediation using ED (excavation and disposal), EKR (electrokinetic remediation), and EZVI (emulsified-zero valent iron), (b) groundwater remediation using PT (pump and treat), and EZVI.

4.3 *Social sustainability assessment*

The social sustainability assessment included a questionnaire that considered indicators such as public health effects, enhancement of housing and recreational activities, changes in perception of the refinery due to the remediation activity, the degree of disruption from the remediation activity, the impact on local businesses, and potential new investments in the area resulting from remediation. Responders were asked to rate these indicators on a scale of 0 to 4, based on the impact of each remediation alternative (0 = unacceptable impact; 1 = diminished; 2 = no impact; 3 = improved; 4 = ideal). Further, the responses were summed to obtain scores for individual criteria, as shown in Table 3. Based on the responses, the extensive operations during the ED were considered to cause significant disruption to the community and further impact recreational activities in the region. The prolonged operations of EKR were also considered to affect economic activities and the perception of the facility. Similarly, PT involves a long operating period and was considered to have economic impacts on the businesses in the region. It is important to note that the assessment is inherently subjective, and the rating scores assigned to the remediation alternatives may vary depending on the individual responses. These results suggest that EKR and EZVI would be more socially sustainable from a social acceptance perspective for soil remediation. At the same time, EZVI is more socially acceptable than PT for groundwater remediation.

Table 3. Social sustainability scores of remediation alternatives.

Social Sustainability Criteria	Soil Remediation			Groundwater Remediation	
	ED	EKR	EZVI	PT	EZVI
Socio-individual	25	35.5	37	30	33
Socio-community	16	23	24	19	26.5
Socio-environmental	26	25	32	20.5	30
Socio-economic	22	35	34	30	24

4.4 *Economic sustainability assessment*

The economic assessment included quantifying the direct and indirect costs associated with it, as well as the potential direct and indirect benefits of adopting a specific remediation alternative. These indirect costs and benefits were quantified using a similar rating scale described previously, on a scale of 0 to 4, based on the level of negative impact, with 0 indicating a severe negative impact and 4 indicating minimal impact. Direct cost estimates for soil remediation were as follows: ED – $1,100,664, EKR – $1,086,200, and EZVI – $817,524. For groundwater remediation, the cost estimates were $979,500 for PT and $684,466 for EZVI. Indirect costs, which included indicators such as land use changes and environmental costs, were higher for ED in soil remediation, a process that involves substantial site alterations and higher environmental impacts, followed by EKR and EZVI. Similarly, PT in groundwater remediation exceeded EZVI in land use disruption and environmental costs. For direct benefits, EKR was considered to generate the highest employment opportunities in soil remediation, whereas ED was considered to have higher post-remediation property value increases. In groundwater remediation, PT outperformed EZVI in terms of employment opportunities provided; however, EZVI achieved higher property value recovery. Indirect benefits included awareness and reputation, which favored EKR in soil remediation and PT in groundwater remediation. Technical competence was higher for ED owing to its efficiency in soil remediation, while EZVI was considered more viable than PT in groundwater remediation. These indicators highlight the trade-offs between direct costs, long-term benefits, and broader economic impacts of the remediation alternatives. Further, these direct and indirect costs and benefits were normalized and integrated to obtain the economic sustainability indices as shown in Figure 5. Results indicate that the EZVI incurred lower costs and higher benefits in both soil and groundwater remediation compared to other alternatives.

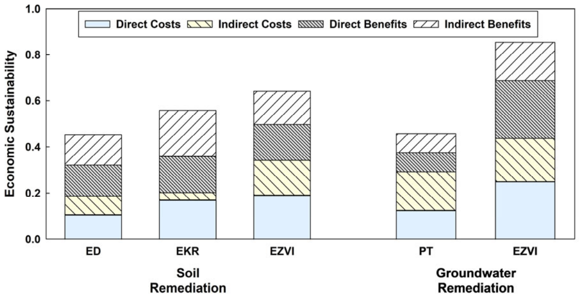

Figure 5. Economic sustainability of soil remediation using ED (excavation and disposal), EKR (electrokinetic remediation), and EZVI (emulsified-zero valent iron), and groundwater remediation using PT (pump and treat) and EZVI.

4.5 *Integrated resiliency and sustainability assessment*

The indicator values from the assessments were integrated to calculate the RSI for the three soil remediation alternatives and two groundwater remediation alternatives. The resiliency scores were incorporated into each of the environmental, social, and economic requirements of sustainability as a criterion. As previously described, this study employed equal weights; however, based on stakeholder preferences, the weights can be adjusted for a preferred comparison. Furthermore, a sensitivity analysis can be conducted by varying weightages to ensure the evaluation aligns with different stakeholder priorities. The RSI scores for soil and groundwater remediation, presented in Figure 6, indicate that EZVI is the most resilient and sustainable alternative for soil and groundwater remediation. In contrast, the other methods cause significant environmental and social impacts and incur higher economic costs.

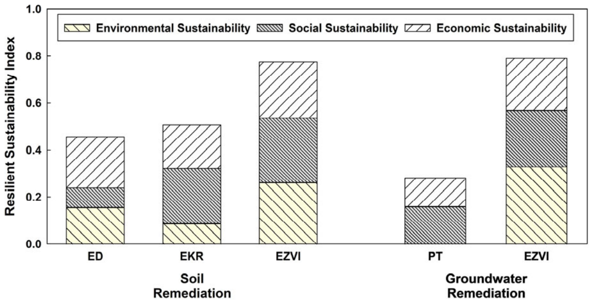

Figure 6. Resilient sustainability indices for soil remediation using ED (excavation and disposal), EKR (electrokinetic remediation), and EZVI (emulsified-zero valent iron), and groundwater remediation using PT (pump and treat) and EZVI.

5 CONCLUSIONS

Remediating contaminated sites presents unique challenges that vary significantly depending on site-specific conditions. With numerous remediation technologies available, selecting the most suitable alternative that aligns with the site's needs is essential. However, ensuring that the chosen remediation effort does not cause significant adverse effects and remains resilient to external stressors is equally imperative. This study provides a comprehensive assessment of the resiliency and sustainability of selected alternatives for remediating contaminated soil and groundwater. Soil remediation alternatives included Excavation and disposal (ED), Electrokinetic remediation (EKR), and emulsified zero valent iron (EZVI), while the groundwater remediation alternatives were pump and treat (PT) and EZVI. The assessment was conducted using the Tiered Quantitative Life Cycle Sustainability and Resiliency (TQUALICSR) framework. The resilience assessment identified ED as the most resilient option compared to EZVI and EKR in soil remediation. However, when sustainability was incorporated, EZVI emerged as the more resilient and sustainable choice. Similarly, EZVI was found to be resilient and sustainable for groundwater remediation compared to PT. Combining resilience and sustainability into a single Resilient Sustainability Index (RSI) offers a comprehensive framework for selecting remediation technologies in environmental management. This approach evaluates the long-term viability of each method under external stressors, while ensuring that remediation efforts align with environmental, social, and economic objectives. By leveraging the RSI, decision-makers can make informed decisions and effectively communicate the benefits of technologies to stakeholders and the communities.

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