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A NEBA- AHP Decision Framework for Sustainable Remediation of Petroleum-Contaminated Soils: A Case Study from Tropical Oil Palm Plantations in Indonesia

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Abstract

This study developed and demonstrated an integrated NEBA–AHP framework for selecting remediation technologies at four petroleum-contaminated sites in active palm oil plantations at four sub-areas in Bengkalis Regency, Riau Province. This study integrates Net Environmental Benefit Analysis (NEBA) and Analytic Hierarchy Process (AHP), as the quantitative component, and guided interviews with 20 respondents across four sub-areas as the qualitative component. Four remediation alternatives were evaluated. The proposed framework consistently discriminated between remediation alternatives across all sub-areas: bioremediation received the highest NEBA-AHP score, while ISCO and excavation with backfilling (Dig & Fill), despite the highest technical effectiveness, were consistently penalized for physical disturbance and socioeconomic disruption. Stakeholders showed strong agreement across sub-areas in ranking preferences and rated bioremediation significantly more acceptable than enhanced natural attenuation. These results illustrate how the framework balances technical, environmental, and social criteria to identify context-appropriate remediation strategies, here favoring bioremediation under the evaluated conditions. The NEBA-AHP framework is transferable to other contaminated sites, provided that criterion weights are re-elicited through local expert panels reflecting site-specific regulatory, ecological, and socioeconomic conditions.

Keywords: *sustainable remediation, multi-criteria decision analysis, petroleum-contaminated soil, net environmental benefit analysis, analytic hierarchy process*

Abstrak

Penelitian ini mengembangkan dan mendemonstrasikan kerangka kerja terintegrasi NEBA–AHP untuk memilih teknologi remediasi pada empat lokasi tanah tercemar minyak bumi di perkebunan kelapa sawit aktif, pada empat subwilayah di Kabupaten Bengkalis, Provinsi Riau. Penelitian ini mengintegrasikan Net Environmental Benefit Analysis (NEBA) dan Analytic Hierarchy Process (AHP) sebagai komponen kuantitatif, serta wawancara terpandu dengan 20 responden di empat subwilayah sebagai komponen kualitatif. Empat alternatif remediasi dievaluasi. Kerangka kerja yang diusulkan secara konsisten mampu membedakan alternatif remediasi di seluruh subwilayah: bioremediasi memperoleh skor NEBA-AHP tertinggi, sementara ISCO serta penggalian dengan penimbunan kembali (Dig & Fill), meskipun memiliki efektivitas teknis tertinggi, secara konsisten mendapat penalti akibat gangguan fisik dan disrupsi sosial-ekonomi. Para pemangku kepentingan menunjukkan kesepakatan yang kuat antarsubwilayah dalam peringkat preferensi, dan menilai bioremediasi jauh lebih dapat diterima dibandingkan atenuasi alami yang ditingkatkan (enhanced natural attenuation). Hasil ini menggambarkan bagaimana kerangka kerja tersebut menyeimbangkan kriteria teknis, lingkungan, dan sosial untuk menentukan strategi remediasi yang sesuai dengan konteks, dan dalam kajian ini memilih bioremediasi sebagai pilihan terbaik pada kondisi yang dievaluasi. Kerangka kerja NEBA-AHP ini dapat diterapkan pada lokasi tercemar lain, dengan syarat bobot kriteria dielisitasi ulang melalui panel pakar lokal yang mencerminkan kondisi regulasi, ekologi, dan sosial-ekonomi spesifik lokasi.

Kata Kunci: *remediasi berkelanjutan, analisis keputusan multi-kriteria, tanah tercemar minyak bumi, analisis manfaat lingkungan bersih, proses hierarki analitik*

1. Introduction

Petroleum-contaminated soil from past exploration and production continues to pose major cleanup challenges in Southeast Asia's oil-producing areas, as documented in other tropical, resource-dependent settings [1], [2]. Managing this contamination raises a less-addressed question: whether the remediation intervention itself, not only the residual contamination, disrupts the livelihoods of communities dependent on the affected land. In Riau Province, Indonesia, residual Total Petroleum Hydrocarbon (TPH) contamination persists on land now used for oil palm farming; the main issue is not the level of chemical risk, but whether people will accept cleanup that disrupts productive land use. Indonesian regulation requires cleanup of such soil, but risk-based tools like RBCA Tier 2 only set thresholds and do not compare the environmental and social pros and cons of cleanup options, which instead requires weighing technical effectiveness, side effects, long-term risks, costs, and disruption to local livelihoods [3]. Net Environmental Benefit Analysis (NEBA) compares environmental services gained against cleanup's negative effects. Adding the Analytic Hierarchy Process (AHP) expands expert opinion beyond simple weighting and checks preference consistency [4], making decisions more transparent than qualitative methods alone [5]. AHP-based frameworks are already used in petroleum-contaminated soil management, such as selecting phytoremediator species at shale-gas and oil-field sites [6], yet integration with NEBA remains largely unexplored.

Most NEBA studies come from developed countries and focus on marine spills [7] or offshore decommissioning [8], with little systematic use for tropical farmland contamination. Social factors are the least considered criterion in soil-cleanup MCDA studies [9], partly because they are harder to measure than costs or technical results [10]; perceived external imposition of cleanup measures is also known to drive acceptance or resistance [11]. This study addresses these gaps using a combined NEBA-AHP approach to compare four cleanup options, Enhanced Natural Attenuation, Bioremediation, In-Situ Chemical Oxidation, and Dig & Fill, at four TPH-contaminated sites in Bengkalis Regency, Riau, assessing whether quantitative scores align with community acceptance.

2. Material and Methods

Study site and sub-areas characterization

The study was conducted at four petroleum-contaminated sub-districts in Bengkalis Regency, Riau Province, Indonesia: Bekasap South 2, West Pinggir, Sebanga North 2, and South Pinggir 3, primarily characterized by palm oil plantations and temporary farming settlements. The sites cover approximately 38,420 m² of contaminated land, ranging from 213 m² (Sebanga North 2) to 19,219 m² (Bekasap South 2). A four-phase mixed-methods approach was used: (1) site characterization and risk-based screening levels (RBSL), (2) quantitative NEBA-AHP scoring, (3) qualitative structured interviews, and (4) integrated statistical analysis, following the "concurrent embedded" model [12] in which qualitative data provide contextual support for quantitative results.

Soil and water quality analysis

Soil samples were collected at four depth intervals (0–30, 30–60, 60–90, and 90–120 cm), focusing on C_5–C_{36} TPH fractions, following SNI 03-6802-2002. Sampling points were determined by contamination extent and accessibility: Bekasap South 2 (2), West Pinggir GS (2), Sebanga North 2 (1), and South Pinggir 3 (3). All soil samples and surface water at three of the four sites were analyzed by PT ALS Indonesia (KAN accreditation LP-091-IDN, valid May 25, 2022 to May 22, 2027); water results were screened against Government Regulation No. 22 of 2021, Annex VI, Class II. Field-level QA/QC procedures were not documented. Each depth-interval result represents a composite sample; observed differences reflect between-sample variation.

Risk-based screening level (RBSL) calculation

Site-specific Tier 2 Risk-Based Screening Levels (RBSLs) were established per the ASTM RBCA framework for non-residential worker receptors exposed via oral ingestion, inhalation, and skin contact to TPH fractions C_6–C_{44}, consistent with previous applications at petroleum-contaminated sites in Indonesia [13]; exposure parameters followed USEPA [14]. The RBSL functions as a health-risk-based ceiling confirming the exposure a receptor can tolerate while keeping the Hazard Index below 1, distinct from the statutory 1,000 mg/kg soil-quality standard in GR 22/2021 (Annex I): the RBSL establishes whether a site is safe for its current use, while the statutory standard is the fixed legal compliance target regardless of site-specific exposure. TPH toxicity assessment is inherently complex, since reference-dose (RfD) values differ by fraction, contribute the greatest uncertainty to RBSL results, up to an order of magnitude [15], and remain actively debated, with some recent work arguing the values historically used are overly conservative for medium-carbon-range fractions [16], [17].

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Net environmental benefit analysis (NEBA) with AHP weighting

The NEBA framework was applied using a matrix approach to mitigate spill consequences, scoring the effect of each remediation alternative across technical, ecological, economic, and socioeconomic resources to ensure transparent assessment procedures [3]. This approach is broadly consistent with the Spill Impact Mitigation Assessment (SIMA) framework's operational scoring logic [18], [19]; however, quantifying net benefit through dose-response relationships requires a recovery-trajectory model, which this study adds to complement SIMA's sensitivity-weighted scoring. For each remediation alternative, an aspect score was calculated by multiplying the impact score by the remediation score. The impact score reflects the level of ecosystem disturbance expected if natural attenuation were left to proceed without any active intervention (0 = neutral, 1 = low, 2 = moderate, 3 = high). The remediation score reflects whether a given intervention provides a benefit or causes additional harm relative to that baseline, and whether this effect is temporary, permanent, or cumulative over time. The aspect score for each criterion was calculated as the sum of the products of the impact and remediation scores for all relevant ecosystem components within that criterion. The final NEBA score was calculated using Equation (1):

$$NEBA\ Score = \Sigma\ (w_j \times Aspect\ Score_j) \qquad (1)$$

In this equation, w_j represents the weight for criterion j derived from the AHP. The six evaluation criteria are technical effectiveness, remediation duration, costs, environmental impacts, socioeconomic and cultural impacts, and residual risk.

A hypothetical recovery model, adapted from the trajectory concept of Hawes et al. [20], was used to construct the spill-impact mitigation matrix for each alternative at each sub-area. Both components rely on secondary literature rather than site-specific measurement: ecological recovery, expressed as land-cover change scaled to the contaminated area, and chemical exposure reduction across the seven scenario combinations evaluated.

The Analytic Hierarchy Process [21] was used to derive priority weights for the six evaluation criteria through structured pairwise comparisons on a nine-point absolute rating scale, breaking the decision problem into a hierarchy of objectives, criteria, and alternatives [4]. Matrices were compiled by eight experts: risk assessment (n = 2), remediation specialists (n = 2), industry stakeholders (n = 2), and academia (n = 2). This weighting vector reflects the panel's judgments for the Bengkalis sub-areas; applying the framework elsewhere would require site-specific AHP elicitation with locally constituted experts, potentially yielding a different weight vector and ranking.

At each sub-area, four remediation alternatives were evaluated: (1) Enhanced Natural Attenuation (ENA), an in-situ approach combining selective bio-stimulation, phytoremediation with hydrocarbon-tolerant vegetation, on field trials reporting TPH reductions of roughly 10–83% depending on plant species and soil amendment [22], [23]; (2) bioremediation through bio-stimulation and bioaugmentation [24], which still requires soil aeration to support microbial activity; (3) in-situ chemical oxidation (ISCO) using hydrogen peroxide injection, whose oxidative mechanisms against aliphatic and aromatic fractions via Fenton and Fenton-like reactions have been extensively reviewed [25]; and (4) excavation and backfilling (Dig & Fill), for ex situ removal and off-site disposal of contaminated soil.

First-order degradation kinetics characterized expected TPH decline for each biological alternative: ENA's rate constants [26] treated as conservative upper bounds; bioremediation applied to the in-situ biostimulation-bioaugmentation scenario at all four sub-areas [27]; ISCO's removal efficiency approximated as a removal-fraction proxy [28]; and Dig & Fill's rate [29] combined with expert judgment.

Qualitative data collection

The interviews were conducted using a structured questionnaire that covered six thematic areas, namely (1) demographic profile and dependence on land use, (2) awareness of and exposure to petroleum contamination, (3) perceived effects on environmental quality, health, and socioeconomic activities, (4) measures taken in response to the contamination, (5) knowledge of remediation methods, and (6) assessment of the social acceptability of four remediation approaches on a four-point Likert scale (1 = unacceptable; 4 = highly acceptable). Qualitative data were analyzed descriptively and triangulated with quantitative NEBA-AHP scores, following the mixed-methods integration procedures described by Creswell and Plano Clark [12]. Respondents (n=20) were selected through a targeted sample of stakeholders directly affected by or knowledgeable about the contaminated sub-areas, identified during a single field visit (May 3, 2025) and including landowners, plantation workers, local vendors, and village-level oversight members. All participants gave written, voluntary informed consent before the structured interview began.

Statistical analysis

Across four sub-areas and four remediation alternatives (n = 16 combinations), four complementary statistical tests were applied: Kendall's coefficient of concordance to assess ranking agreement among sub-areas [30]; the Friedman test for differences among alternatives, given its mathematical equivalence to Kendall's W, with Wilcoxon signed-rank post-hoc comparisons and Bonferroni correction where applicable [31]; a one-sided paired Wilcoxon signed-rank test comparing stakeholder acceptability of bioremediation versus enhanced natural attenuation (n = 20 paired respondents; [32]); and one-at-a-time AHP weight perturbation (±10%/±20%, 96 scenarios) with crossover analysis to test ranking robustness.

3. Results and Discussion

TPH Contamination Levels and SSTL Exceedance

TPH concentrations at all four sub-areas showed marked spatial and vertical variability (Table 1), attributed to weathered crude oil that underwent partial natural degradation, preferentially losing lighter fractions while heavy aliphatics (C_{16}–C_{35}) persisted. Because Sebanga North 2 alone met the stricter statutory standard (1,000 mg/kg, GR 22/2021) while the other three sub-areas retained at least one exceedance, most severely at West Pinggir sampling point 1 (0–30 cm), the marginal risk-reduction value of active remediation differed structurally between Sebanga North 2 and the remaining sub-areas before any NEBA-AHP weighting was applied.

Table 1. The highest TPH concentration at each sublocation (mg/kg dry weight) across sampling depths and SSTL comparison

Sub-areas	Sampling Point	The highest TPH concentration at each sublocation (mg/kg)				SSTL (mg/kg)
		0–30 cm	30–60 cm	60–90 cm	90–120 cm	
West Pinggir	Point 1	11,808.2	8,721.9	3,665.3	3,634.3	24,473
	Point 2	541	966.1	966.1	362.9	
Sebanga North 2	Point 1	570	338	-	-	15,739
Bekasap South 2	Point 1	710	7,496	1,211	5,716	20,349
	Point 2	798	523	489	3,016	
South Pinggir 3	Point 1	2,156.6	2,141.7	881.1	2,032.9	18,662
	Point 2	-	-	300	642	

Notes: "–" = no laboratory result for that depth interval. Total TPH = sum of aromatic and aliphatic fractions (C_5–C_{36}), analyzed by PT ALS Indonesia (USEPA 3546 preparation; USEPA 8015C for C_{10}–C_{36}). Limits of reporting: 5.0 mg/kg (light fractions, C_5–C_{10}) and 40 mg/kg (heavy fractions, C_{10}–C_{36}); these fraction-level LORs apply to the individual results underlying the aggregated Total TPH values shown.

AHP Weights and NEBA Scoring

The pairwise comparison using the Analytic Hierarchy Process (AHP) method yielded a consistency ratio of 0.64%, confirming the internal consistency of the experts' assessments within the weighting matrix. In the resulting weighting hierarchy, technical effectiveness (w = 0.3206) was given the highest priority, followed by socioeconomic and cultural impact (w = 0.2424), environmental impacts (w = 0.2103), the duration of remediation (w = 0.1213), residual risk (w = 0.0713), and costs (w = 0.0341). Figure 1 shows the engineering workflow that summarizes the complete NEBA–AHP implementation process from site investigation to technology selection. The NEBA-AHP scores for all sub-areas and alternatives are shown in **Table 2**.

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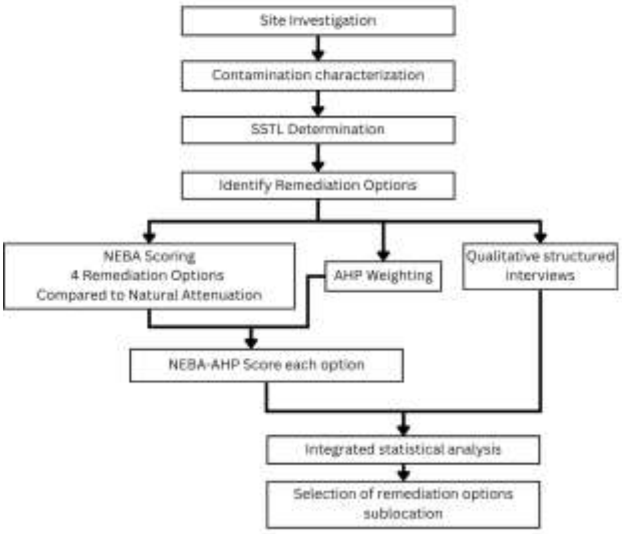

Figure 1. NEBA-AHP workflow

Table 2. NEBA-AHP scores for 4 analysis units and 4 remediation options

Evaluation Aspect (weight)	West Pinggir				Bekasap South 2				South Pinggir 3				Sebanga North 2			
	ENA	**Bio**	**ISCO**	**D&F**	**ENA**	**Bio**	**ISCO**	**D&F**	**ENA**	**Bio**	**ISCO**	**D&F**	**ENA**	**Bio**	**ISCO**	**D&F**
Effectiveness (0.3206)	0.64	1.28	1.92	1.92	0.64	1.28	1.92	1.92	0.64	1.28	1.92	1.92	0.32	0.64	0.96	0.96
Environmental Impact (0.2103)	2.52	2.31	-3.15	-2.94	2.52	2.31	-3.15	-2.94	2.73	2.73	-4.21	-3.79	2.73	2.73	-4.21	-3.79
Cost (0.0341)	0.07	0.07	-0.10	-0.10	0.07	0.07	-0.10	-0.10	0.07	0.07	-0.10	-0.10	0.07	0.07	-0.07	-0.07
Socio-Economic & Cultural (0.2424)	1.45	1.45	-0.73	-1.45	1.45	1.45	-1.45	-2.42	1.45	1.45	-1.45	-2.42	1.45	1.45	-1.45	-2.18
Duration (0.1213)	0.24	0.24	0.49	0.73	0.24	0.24	0.49	0.73	0.24	0.24	0.49	0.73	0.12	0.12	0.24	0.36
Residual Risk (0.0713)	1.07	1.07	-0.93	-0.29	1.07	1.07	-0.93	-0.43	0.93	1.00	-0.64	-0.21	0.78	0.78	-0.50	-0.36
NEBA-AHP Score	6.00	6.43	-2.50	-2.13	6.00	6.43	-3.23	-3.25	6.07	6.78	-4.00	-3.87	5.48	5.80	-5.02	-5.07
Rank	2	1	4	3	2	1	3	4	2	1	4	3	2	1	3	4

Notes: ENA = Enhanced Natural Attenuation; Bio = Bioremediation (bio-stimulation–bioaugmentation); ISCO = In-Situ Chemical Oxidation; D&F = Dig & Fill (treatment by third party). Rank reflects ordinal position (1 = highest NEBA-AHP score, 4 = lowest) within each sub-area.

Chemical Exposure Reduction Trajectories

Chemical exposure reduction model (**Figure 2**), using % removal described in Methods, showed bioremediation reaching the 1,000 mg/kg statutory target within 5–7 months (optimistic) to 6–9 months (pessimistic) at the most contaminated sub-area (West Pinggir), compared with 10–14 months for ENA. ISCO's oxidation TPH removal and Dig & Fill's immediate excavation both achieve faster nominal chemical reduction, but this is offset in the NEBA score by their substantially greater ecological disturbance rather than the exposure risk.

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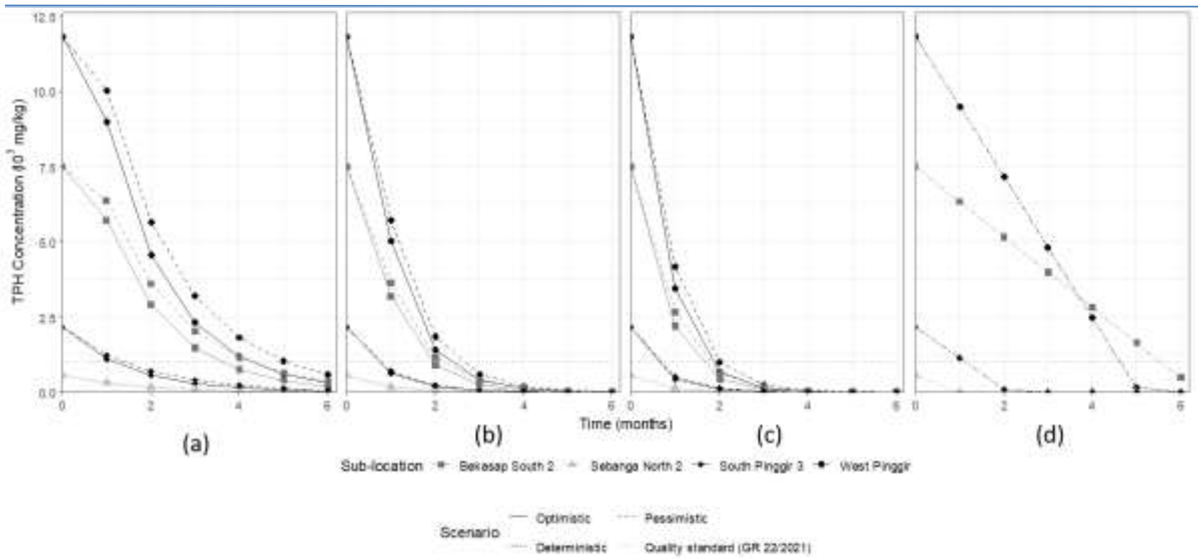

Figure 2. Chemical exposure reduction trajectories for (a) Enhanced Natural Attenuation, (b) Bioremediation on-site, (c) ISCO, and (d) Ex-Situ Dig & Fill at each sub-area

Friedman Test for Score Differences and Wilcoxon Signed-Rank Test for Social Acceptability

Kendall's W demonstrated near-perfect ranking agreement among sub-areas ($W = 0.900$, $\chi^2 = 10.800$, $df = 3$, $p = 0.013$), and the Friedman test confirmed significant differences among alternatives on the same rank data; post-hoc comparisons were not interpreted given the limited number of blocks. Bioremediation received significantly higher acceptability ratings than ENA (mean 3.95 vs 1.60 of 4; paired Wilcoxon $V = 210.0$, $p < 0.001$), with median acceptability of 2 for the ISCO proxy and 3 for the Dig & Fill proxy.

Boundary conditions: Bengkalis-specific variables to re-assess before adopting this framework elsewhere

Beyond noting that the numerical weight vector is not intended to be transferred, it is possible to identify from the results above which characteristics of the Bengkalis sub-areas actually drove the AHP weights and the NEBA ranking. Table 3 summarizes these as boundary conditions: an adopter applying this framework at a different contaminated site should re-assess each of these variables for their own context rather than assume the Bengkalis outcome will recur.

Table 3. Boundary conditions identified from the Bengkalis case and the corresponding site characteristics that an adopting study should reassess when applying the NEBA-AHP framework elsewhere.

Variable	What an adopting site should re-assess
Remediation-cost liability regime	This mechanism is jurisdiction-bound to Indonesia. Adopters elsewhere must identify their own applicable liability regime (e.g., polluter-pays statutes, cost-recovery schemes, or the absence of one) before assuming a similarly low cost weight.
Land-use status and livelihood dependency	Adopters should check whether the target land use is active/income-generating or idle, and whether it has a resident stakeholder base; an active but unpopulated site still carries livelihood stakes that a site like West Pinggir does not.
Contaminant weathering stage, fraction profile, and characterization status	Assess both the contamination's age/weathering stage/carbon-fraction profile and whether the site has undergone formal delineation confirming remediation is warranted; sites without completed delineation are not ready for this framework.
Scale and depth-stratified extent of contamination	Area size drives costing and logistics, not whether remediation is required. Near-surface zones may be cleared directly; deeper zones should first undergo a treatability study. Where a low-intensity outcome (e.g., ENA) is recommended, as at Sebanga North 2, the justification should rest on the site being below the statutory standard.
Hydrogeological and soil conditions	Assess local soil moisture, drainage, and redox conditions, which determine whether a standard bioremediation design is feasible or requires site-specific engineering modification.

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Variable	What an adopting site should re-assess
Purpose of the NEBA-AHP exercise and matching expert-panel composition	Before convening a panel, adopters should first determine which decision the exercise is meant to answer and then compose the panel to match that specific purpose, since a panel suited to one question may not be suited to another.

Site-specific remediation remains essential

The same NEBA-AHP structure yields different site-appropriate recommendations when local contamination levels and land area differ. Sites with different regulatory thresholds, land use, or expert panels would require weight re-elicitation, not merely re-entry of site data; that is the clearest practical illustration, from within this single case study, of how the framework is intended to generalize.

Alignment between quantitative rankings and stakeholder acceptance

Quantitative and qualitative components agreed most strongly on the socioeconomic criterion, where both favored bioremediation. The framework scores ENA favorably for the absence of secondary chemical risk, while some stakeholders view its very passivity as a lingering risk. A similar partial match held for the ISCO/Dig & Fill proxies, whose acceptability tracked the framework's negative environmental and socioeconomic weighting but not fully its social-cost weighting, suggesting the social dimension captures something the quantitative criteria alone do not.

Site-specific management recommendations

Based on the integrated NEBA-AHP scores, the statistical robustness analysis, and the qualitative feasibility assessment, the following sub-area-specific recommendations follow. These recommendations are outputs of applying the Bengkalis-elicited weight vector to each sub-area's own data; they are not intended as generic prescriptions for other sites. Each recommendation below pairs the selected technology with the depth-stratified TPH data and site conditions that shape its engineering design, consistent with the selection-to-implementation pathway outlined above.

West Pinggir: Bioremediation is recommended as the main option. The absence of permanent residents removes the main social feasibility issue, making technical effectiveness and environmental impact the deciding selection criteria. At West Pinggir, Sampling Point 1 (0–30 cm) requires extra attention: despite 85% manual removal, 1,771 mg/kg remains, exceeding the standard of 1,000 mg/kg, confirming that ex situ options alone are insufficient and that bioremediation or a phased approach is needed.

Sebanga North 2: ENA is the most defensible recommendation, as all TPH concentrations already fall below the 1,000 mg/kg statutory standard (GR 22/2021) while the NEBA-AHP margin over bioremediation (5.48 vs 5.80) is small and passive-monitoring costs are lower. These margins indicate preference ordering within Sebanga North 2 rather than a cardinal measure comparable across sub-areas, consistent with the non-transferability of SIMA/NEBA score totals [3]. A structured communication program presenting ENA as actively monitored, rather than passive, is essential to address modest acceptance; if monitoring confirms declining TPH trends, ENA provides an adequate and proportional response.

Bekasap South 2: Bioremediation is recommended, with attention to deeper layers (30–60 cm: 7,496 mg/kg; 90–120 cm: 5,716 mg/kg at Sampling Point 1) and the swampy nature of this sub-area. Soil moisture and redox conditions must be explicitly considered in biostimulation design, as periodically saturated swamp soils limit oxygen and may require additional electron acceptors or aeration [33]. The largest contaminated area (19,219 m^2) requires a phased treatment plan prioritizing hotspot zones.

South Pinggir 3: Bioremediation is recommended, with the highest NEBA-AHP score margin over ENA. The long-resident community profile makes this sub-area the most suitable candidate for community-participatory bioremediation incorporating local monitoring, labor involvement, and regular progress updates, directly addressing acceptability considerations while delivering the highest net ecological benefit.

Study Limitations

Although the NEBA-AHP framework provides a systematic approach for evaluating remediation alternatives, several limitations should be considered. First, results are specific to four sub-areas in one region of Riau Province, with AHP weights and rankings tied to this expert panel and regulatory context; applicability is strongest for similar tropical agricultural settings, not universal. Second, interviewing a larger and more diverse group of stakeholders would improve the results. Third, expert-based AHP weighting is inherently subjective, though the high consistency ratio (0.64%) and stable sensitivity results support the panel's reliability. Fourth, all recovery-time figures are literature-based model projections, not site-measured rates, and may vary with soil texture, weathering, and moisture [34]. Finally, ecological recovery and qualitative impact scores rely on published literature and expert judgment rather than long-term monitoring, which would strengthen confidence if incorporated in future work. Despite these limitations, integrating quantitative NEBA-AHP analysis and stakeholder perceptions provides a reproducible framework for remediation decision-making under tropical agricultural conditions.

4. Conclusion

This study presents a transferable NEBA-AHP decision-support framework for evaluating remediation alternatives at petroleum-contaminated sites where environmental, technical, economic, and social objectives must be weighed simultaneously; however, the specific weights and rankings reported here remain tied to the evaluated jurisdiction and site conditions. The framework was developed and demonstrated across four sub-areas of active oil palm plantation in Bengkalis Regency, Riau Province, Indonesia, contributing a six-criterion NEBA scoring structure, AHP weighting from a multi-background expert panel, and mixed-methods triangulation against stakeholder acceptance data.

Bioremediation consistently scored highest, balancing contaminant reduction, limited ecological disturbance, and social acceptability, followed by ENA, viable where concentrations already sit below thresholds; ISCO and Dig & Fill ranked lower, their technical effectiveness offset by greater environmental and agricultural disruption.

The framework offers a transparent, auditable basis for technology selection: AHP weights and NEBA scores can be reported and defended to regulators, project proponents, and affected communities, and the consistency-checked elicitation procedure can be re-run at a new site rather than re-invented. Its output is a screening decision, not a final design, that identifies which technology to deploy and flags where deeper characterization or a treatability study is warranted before implementation proceeds.

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6. References

[1] G. E. DeVaull, M. Bonte, E. R. Gundlach, et al., "Development and application of human health risk-based screening levels for crude oil affected soils and sediments in the Niger Delta," Integrated Environmental Assessment and Management, vol. 21, no. 5, pp. 1173–1192, 2025, doi: 10.1002/ieam.4952.

[2] I. Pérez-Hernández, S. Ochoa-Gaona, R. H. Adams, M. C. Rivera-Cruz, V. Pérez-Hernández, A. Jarquín-Sánchez, V. Geissen, and P. Martínez-Zurimendi, "Growth of four tropical tree species in petroleum-contaminated soil and effects of crude oil contamination," Environmental Science and Pollution Research, vol. 24, pp. 1769–1783, 2016, doi: 10.1007/s11356-016-7877-5.

[3] P. M. Taylor and M. A. Cramer, "A novel methodology for net environmental benefit analysis (Spill Impact Mitigation Assessment)," International Oil Spill Conference Proceedings, vol. 2017, no. 1, pp. 2454–2474, 2017, doi: 10.7901/2169-3358-2017.1.2454.

[4] A. Ishizaka and E. Mu, "What is so special about the analytic hierarchy and network process?," Annals of Operations Research, vol. 326, no. 2, pp. 625–634, 2023, doi: 10.1007/s10479-023-05412-4.

[5] S. Safarzadeh and H. Jafari, "On the application of multi-criteria decision-making methods in environmental pollution management: A comprehensive systematic review," Environment, Development and Sustainability, 2025, doi: 10.1007/s10668-025-06041-6.

[6] B. Wang, H. Xie, H. Ren, X. Li, L. Chen, and B. Wu, "Application of AHP, TOPSIS, and TFNs to plant selection for phytoremediation of petroleum-contaminated soils in shale gas and oil fields," Journal of Cleaner Production, vol. 233, pp. 13–22, 2019, doi: 10.1016/j.jclepro.2019.05.301.

[7] M. Buber and B. A. Koseoglu, "Bibliometric review and science mapping research of oil spill response," Marine Science and Technology Bulletin, vol. 11, no. 1, pp. 123–134, 2022, doi: 10.1016/j.marpolbul.2022.113931.

[8] J. P. Nicolette, N. A. Nelson, M. K. Rockel, M. L. Rockel, A. N. Testoff, L. L. Johnson, L. D. Williamson, and V. L. G. Todd, "A framework for a net environmental benefit analysis based comparative assessment of decommissioning options for anthropogenic subsea structures: A North

Sea case study," Frontiers in Marine Science, vol. 9, Art. no. 1020334, 2023, doi: 10.3389/fmars.2022.1020334.
[9] F. Abrams, L. Hendrickx, C. Turcanu, L. Sweeck, and J. Van Orshoven, "Multi-Criteria Decision Analysis to Support the Remediation of Polluted Soils: A Review of Case Studies," Land, vol. 13, no. 6, Art. no. 887, 2024, doi: 10.3390/land13060887.
[10] V. Cappuyns, "Inclusion of social indicators in decision support tools for the selection of sustainable site remediation options," Journal of Environmental Management, vol. 184, no. Part 1, pp. 45–56, 2016, doi: 10.1016/j.jenvman.2016.07.035.
[11] D. H. Oughton, "Social and ethical issues in environmental remediation projects," Journal of Environmental Radioactivity, vol. 119, pp. 21–25, 2013, doi: 10.1016/j.jenvrad.2011.08.019.
[12] J. W. Creswell and V. L. Plano Clark, Designing and Conducting Mixed Methods Research, 3rd ed. SAGE Publications, 2018.
[13] I. M. W. Widyarsana and W. C. Dewi, "Risk-based screening level analysis and landfill 'Cap' design of crude oil contaminated soil stockpile in Riau Province, Indonesia," International Journal of Environmental Science and Development, vol. 12, no. 2, pp. 42–50, 2021, doi: 10.18178/ijesd.2021.12.2.1316.
[14] United States Environmental Protection Agency (USEPA), Exposure Factors Handbook: 2011 Edition, EPA/600/R-09/052F. Washington, DC: USEPA, 2011.
[15] T. T. Tsai, C. M. Kao, and R. Y. Surampalli, "Sensitivity analysis of risk assessment at a petroleum-hydrocarbon contaminated site," Journal of Hazardous, Toxic, and Radioactive Waste, vol. 15, no. 2, 2011, doi: 10.1061/(ASCE)HZ.1944-8376.0000067.
[16] G. E. Rice and A. L. Phillips, Provisional Peer-Reviewed Toxicity Values for Complex Mixtures of Aliphatic and Aromatic Hydrocarbons (various CASRNs). Cincinnati, OH: U.S. Environmental Protection Agency, 2022.
[17] C.M. Thompson, V.S. Bhat, G.P. Brorby, and L.C. Haws, "Development of updated RfD and RfC values for medium carbon range aromatic and aliphatic total petroleum hydrocarbon fractions," Journal of the Air & Waste Management Association, vol. 71, no. 12, pp. 1555–1567, 2021, doi: 10.1080/10962247.2021.1974123.
[18] D. Peach and E. Taylor, "Net Environmental Benefit Analysis Embedded Action Planning," Proceedings of the International Oil Spill Conference, 2021. [Online]. Available: https://iosc.kglmeridian.com/view/journals/iosc/2021/1/article-687529.xml
[19] R. J. Wenning, H. Robinson, M. Bock, M. A. Rempel-Hester, and W. Gardiner, "Current practices and knowledge supporting oil spill risk assessment in the Arctic," Marine Environmental Research, vol. 141, pp. 289–304, 2018, doi: 10.1016/j.marenvres.2018.09.006.
[20] I. Hawes, C. Howard-Williams, J. Webster-Brown, and C. Poirot, "Restoration of legacy contaminated sites in Antarctica: Lessons from Vanda Station, McMurdo Dry Valleys," Polar Record, vol. 61, Art. no. e2, 2025, doi: 10.1017/S0032247424000354.
[21] T.L. Saaty, "Decision making with the analytic hierarchy process," International Journal of Services Sciences, vol. 1, no. 1, pp. 83–98, 2008, doi: 10.1504/IJSSCI.2008.017590.
[22] B. F. Nero, "Phytoremediation of petroleum hydrocarbon-contaminated soils with two plant species: Jatropha curcas and Vetiveria zizanioides at Ghana Manganese Company Ltd," International Journal of Phytoremediation, vol. 23, no. 2, pp. 171–180, 2021, doi: 10.1080/15226514.2020.1803204.
[23] T.G. Ambaye, A. Chebbi, F. Formicola, S. Prasad, F.H. Gomez, A. Franzetti, and M. Vaccari, "Remediation of soil polluted with petroleum hydrocarbons and its reuse for agriculture: Recent progress, challenges, and perspectives," Chemosphere, vol. 293, Art. no. 133572, 2022, doi: 10.1016/j.chemosphere.2022.133572.
[24] B. A. Mekonnen, T. A. Aragaw, and M. B. Genet, "Bioremediation of petroleum hydrocarbon contaminated soil: a review on principles, degradation mechanisms, and advancements," Frontiers in Environmental Science, vol. 12, Art. no. 1354422, 2024, doi: 10.3389/fenvs.2024.1354422.
[25] Y. Dai and Z. Liu, "Research progress on remediation of total petroleum hydrocarbons in soil by chemical oxidation, a review," Frontiers in Environmental Engineering, vol. 4, Art. no. 1532795, 2025, doi: 10.3389/fenve.2025.1532795.
[26] M. Andreolli, S. Lampis, P. Brignoli, and G. Vallini, "Bioaugmentation and biostimulation as strategies for the bioremediation of a burned woodland soil contaminated by toxic hydrocarbons: A comparative study," Journal of Environmental Management, vol. 153, pp. 121–131, 2015, doi: 10.1016/j.jenvman.2015.02.007.

[27] Q. Helmy and E. Kardena, "Enhancing field-scale bioremediation of weathered petroleum oil-contaminated soil with biocompost as a bulking agent," Case Studies in Chemical and Environmental Engineering, vol. 9, pp. 100735, 2024, doi: 10.1016/j.cscee.2024.100735.
[28] I. Kim and M. Lee, "Pilot scale feasibility study for in-situ chemical oxidation using H2O2 solution conjugated with biodegradation to remediate a diesel-contaminated site," Journal of Hazardous Materials, vol. 241–242, pp. 173–181, 2012, doi: 10.1016/j.jhazmat.2012.09.022.
[29] S. Kuppusamy, T. Palanisami, M. Megharaj, K. Venkateswarlu, and R. Naidu, "Ex situ Remediation Technologies for Environmental Pollutants: A Critical Perspective," in Reviews of Environmental Contamination and Toxicology, vol. 236, P. de Voogt, Ed. Cham: Springer, 2016, doi: 10.1007/978-3-319-20013-2_2.
[30] F. Franceschini and D. Maisano, "Aggregating multiple ordinal rankings in engineering design: The best model according to Kendall's coefficient of concordance," Research in Engineering Design, vol. 32, pp. 91–103, 2021, doi: 10.1007/s00163-020-00348-3.
[31] R. Eisinga, T. Heskes, B. Pelzer, and M. Te Grotenhuis, "Exact p-values for pairwise comparison of Friedman rank sums, with application to comparing classifiers," BMC Bioinformatics, vol. 18, no. 1, pp. 68, 2017, doi: 10.1186/s12859-017-1486-2.
[32] Y. Park, "Optimal two-stage group sequential designs based on the Mann-Whitney-Wilcoxon test," PLOS ONE, vol. 20, no. 2, pp. e0318211, 2025, doi: 10.1371/journal.pone.0318211.
[33] M. Romantschuk, K. Lahti-Leikas, M. Kontro, P. Galitskaya, H. Talvenmäki, S. Simpanen, J. A. Allen, and A. Sinkkonen, "Bioremediation of contaminated soil and groundwater by in situ biostimulation," Frontiers in Microbiology, vol. 14, Art. no. 1258148, 2023, doi: 10.3389/fmicb.2023.1258148.
[34] L. Huang, H. Wang, and S. D. Siciliano, "Insights into the declined efficacy of in situ deep soil benzene biostimulation: An investigation across four sites over three years," Land Degradation & Development, vol. 36, no. 17, pp. 5927–5938, 2025, doi: 10.1002/ldr.70046.