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Collaborative Strategies for Sustainable Remediation of Hydrocarbon-Contaminated Soils in Rainforest Areas

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Abstract: Remediating hydrocarbon-contaminated soils in rainforest ecosystems poses complex challenges, requiring strategies that balance ecological restoration with long-term sustainability. This study aimed to analyze stakeholder dynamics and identify collaborative approaches to support sustainable remediation in the Taman Hutan Raya Sultan Syarif Hasyim (TAHURA SSH) area in Sumatra. The Matrix of Alliances and Conflicts: Tactics, Objectives, and Recommendations (MACTOR) method was applied to examine interactions among eleven stakeholder groups. Data were collected through purposive interviews and focus group discussions to evaluate influence, dependence, and consensus across these groups. The findings revealed that Pertamina Hulu Rokan (PHR) and contractors function as central actors with the highest influence in advancing remediation practices. Conversely, local communities exhibited limited influence, suggesting their potential marginalization in decision-making processes. Although strong consensus was observed on ecological priorities—such as ecosystem restoration, long-term sustainability, and minimizing environmental impact—significant divergence regarding cost-effectiveness exposed underlying tensions between economic efficiency and environmental objectives. Sustainable remediation in rainforest ecosystems requires collaborative and inclusive strategies that foster partnerships among the private sector, government institutions, and local communities. These results provide practical implications for policymakers to develop environmentally responsible and socially equitable remediation frameworks in fragile ecosystems.

Keywords: Hydrocarbon; Remediation; Rainforest; Sustainability; Strategy

1 Introduction

Soil contamination by hydrocarbons represents a major environmental challenge [1], particularly in rainforest ecosystems where biodiversity is highly vulnerable to pollutants. Hydrocarbons disrupt nutrient cycling, alter microbial community structures, and inhibit plant growth [2–4] leading to long-term ecological degradation [5]. In these settings, remediation is complex due to the intricate ecological interactions among diverse flora, fauna, and microorganisms. Consequently, environmentally sensitive approaches such as bioremediation (including phytoremediation and microbial-based methods) are prioritized because they align with existing biological processes. In contrast, conventional techniques like incineration or excavation are often unsuitable due to their destructive impacts on fragile environments. Biostimulation and bioaugmentation present promising alternatives, as they accelerate natural degradation processes without requiring harsh chemical inputs [6, 7]. However, the effectiveness of bioremediation in rainforest soils depends on site-specific factors, including soil composition, moisture content, and hydrocarbon type, necessitating comprehensive site assessments and context-specific implementation strategies [8].

In the study area, approximately six hectares of hydrocarbon-contaminated soil have been identified within forested land. This contamination has severely degraded local ecosystems, causing significant loss of vegetation and threatening wildlife populations. Dense canopy cover further complicates access and hinders remediation activities. Environmental experts have expressed concerns regarding long-term threats to groundwater quality and the potential migration of contaminants into adjacent aquatic systems. To address this, local authorities initiated detailed assessments, employing aerial surveys and satellite imagery to delineate the extent of contamination and design targeted remediation strategies. Understanding stakeholder roles is essential for advancing sustainable remediation practices. Active participation from local communities, government institutions, and industry actors enables the identification of priorities, concerns, and indigenous knowledge critical to the remediation process [9]. Inclusive decision-making reduces potential conflicts, fosters broad-based support, and can generate innovative solutions that reconcile ecological restoration with economic and social imperatives [10]. Such approaches ultimately strengthen the long-term impact and resilience of remediation initiatives [11].

Despite these technical efforts, a limited understanding persists regarding how stakeholder involvement shapes the success and sustainability of remediation interventions. This knowledge gap constrains the development of effective strategies for engaging local communities and other relevant actors. Incorporating stakeholder perspectives enhances remediation practices by ensuring they are contextually appropriate, socially acceptable [12], and supported by local populations [13, 14]. Therefore, this study aimed to analyze key stakeholders, assess their respective roles, and identify collaborative strategies to advance the sustainable remediation of hydrocarbon-contaminated rainforest soils.

2 Materials and Methods

2.1 Study Site

The research was conducted in Taman Hutan Raya Sultan Syarif Hasyim (TAHURA SSH), located at 0°37'–0°44' N and 101°20'–101°28' E (Figure 1). The study area encompassed six hectares of soil contaminated by hydrocarbon leaks. This site is a critical biodiversity hotspot, hosting 127 native plant species, 42 bird species, and several endangered mammals, including the Sumatran elephant and tiger [15]. Beyond its role as a carbon sink, TAHURA SSH provides vital hydrological regulation and serves as a regional center for scientific research and environmental education.

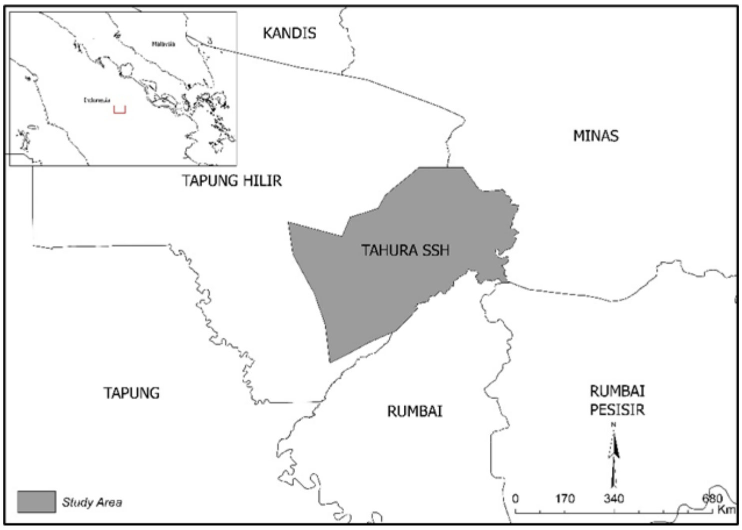

Figure 1. Research location

2.2 Data Collection and Analysis

This study employed a case study approach. Data were gathered through purposive interviews and focus group discussions with key informants selected based on their direct involvement in forest soil remediation. The focus group discussions aimed to determine the strategic goals, interests, and strengths of each stakeholder.

Five strategic goal factors were formulated to assess stakeholder positions: (i) involvement in mitigation education, (ii) participation in restoration management policies, (iii) involvement in spatial planning policies, (iv) readiness for mitigation actions, and (v) commitment to budget allocation. A questionnaire was utilized to evaluate coordination relationships, measuring responses on a 9-point Likert scale (from -4 to 4).

To elucidate stakeholder interactions, the study applied the Matrix of Alliances and Conflicts: Tactics, Objectives, and Recommendations (MACTOR) method [16, 17]. This prospective analysis tool systematically examines actor relationships by assessing: (1) power relations (measured on a scale of 0 to 4); (2) strategic attitudes toward goals (supportive, neutral, or opposed); and (3) the relative importance of goals to each actor.

The stages of the MACTOR analysis (Figure 2) consist of the following: (1) identifying the actors and determining a set of goals; (2) describing the power relations of actors as measured on a scale of 0 (no influence) to 4 (powerful influence); (3) describing the attitude (level of resistance) of actors towards goals as measured by a scale of (+) supports, (0) neutral, and (-) opposes; and (4) assessing the importance of goals for actors as measured on a scale of 0 (not important) to 4 (very important) [18, 19].

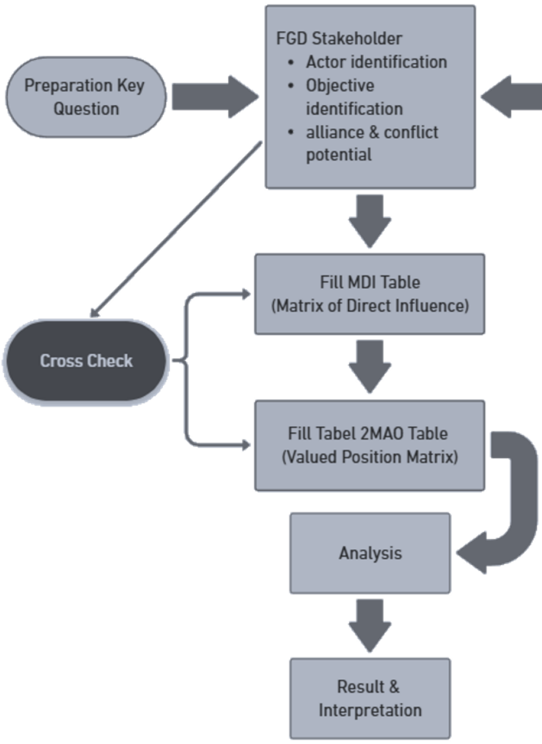

Figure 2. Step of Matrix of Alliances and Conflicts: Tactics, Objectives, and Recommendations (MACTOR) analysis

3 Results and Discussion

3.1 Identification of Stakeholders and Interaction Patterns in Oil-Contaminated Soil Remediation

The identification results from the focus group discussions revealed 11 stakeholders important for maintaining the sustainability of the oil-contaminated soil recovery system in TAHURA SSH (Table 1). Several objectives were also identified and grouped into ecological, economic, and social dimensions (Table 2).

Restoring oil-contaminated soils in forest areas relies heavily on collaboration among various stakeholders, including government agencies, industry players, and local communities. Stakeholder collaboration is essential for effectively managing recovery efforts, as it brings together the diverse expertise and resources required for successful outcomes [20].

Table 1. List of stakeholders in the oil-contaminated soil recovery system

No.	Stakeholder	Symbol	Role
1	Directorate General of Waste and Hazardous Waste Management	DirB3	Responsible for waste, hazardous, and toxic material management
2	Natural Resources Conservation Center	BKSDA	Management of conservation areas and ecosystem preservation
3	KPHP TAHURA Minas	KPHPMinas	Forest management unit under the Department of Environment
4	University	University	Provides advice and input in remediation process
5	Oil and gas company	Pertamina Hulu Rokan (PHR)	Responsible for managing hazardous waste
6	Local villagers	Locvillager	Community members potentially employed as labor
7	Village government	Villagegov	Mediates remediation work with local communities
8	Regency government	Regencygov	Assists with labor administration and supervision
9	Non-government organization	NGO	Independent monitor
10	Contractor	Contractor	Executes recovery activities
11	Electronic and mass media	Media	Raises awareness and bridges involved parties

Table 2. List of objectives in the oil-contaminated soil recovery system

No.	Objective	Symbol	Dimension
1	Ecosystem restoration	ecosystem	Ecology
2	Long-term sustainability	longsustain	Ecology
3	Minimizing environmental impact	linimpact	Ecology
4	Cost-effectiveness	cost	Economic
5	Job creation	job	Economic
6	Sustainable land use	sustland	Economic
7	Community engagement	comm	Social
8	Public health protection	pubhealth	Social
9	Innovative solutions	innovsol	Social

Community engagement is essential in this process, as it ensures that local knowledge and needs are integrated into recovery strategies. Involving communities fosters a sense of ownership and increases the effectiveness of remediation practices by aligning them with the specific ecological and social contexts of the affected area. Natural resource trustees play a crucial role in this framework, as they are responsible for assessing damage and overseeing the restoration of contaminated ecosystems, thus ensuring compliance with environmental laws. Their role is complemented by collaborative restoration efforts that involve joint initiatives among stakeholders to share resources and improve reclamation practices. Such partnerships can lead to innovative solutions and a more efficient use of financial and technical resources. This engagement is critical for ecological restoration, where the goal is to repair damaged ecosystems and restore the relationship between people and nature.

The Matrix of Direct and Indirect Influences (MDII) in Table 3 identified the Contractor (Ii = 108) and Pertamina Hulu Rokan (PHR) (Ii = 107) as the most influential actors in the system. Their high dependency scores (Di = 88 and Di = 91, respectively) indicate that while they lead technical execution, their success is legally and operationally tied to government regulatory frameworks. Government bodies like Directorate General of Hazardous Waste Management (Direktorat Jenderal Pengelolaan Limbah, Sampah, dan Bahan Berbahaya dan Beracun, DirB3), Natural Resources Conservation Agency (Balai Konservasi Sumber Daya Alam, BKSDA), and KPHP Minas also maintained high influence, confirming their roles as primary regulators. Conversely, the analysis highlighted a significant marginalization of local communities. These actors exhibited low influence and dependency, suggesting that their local ecological knowledge is currently underutilized in formal decision-making processes.

PHR and the Contractor's high influence and dependence underscore their responsibility in prioritizing sustainable practices. Their decisions regarding remediation techniques, site management, and community engagement significantly impact a project's sustainability.

Table 3. Matrix of direct and indirect influences (MDII)

MDII	DirB3	BKSDA	KPHP	Univ.	PHR	Loccomm	Villagegov	Regencygov	NGO	Contractor	Media	Ii
DirB3	13	15	15	5	14	3	4	6	8	14	7	91
BKSDA	13	14	14	5	13	3	4	6	8	13	7	86
KPHPMinas	12	14	13	5	13	3	4	6	8	12	7	84
University	5	5	5	4	5	2	2	2	5	5	5	41
PHR	16	19	19	5	21	3	5	6	8	19	7	107
Loccomm	2	2	2	2	2	2	2	2	2	2	2	20
Villagegov	4	4	4	3	4	3	3	3	3	4	3	35
Regencygov	6	6	7	5	7	2	4	3	6	7	6	56
NGO	7	7	7	4	7	2	3	4	5	6	6	53
Contractor	16	19	19	5	20	3	5	6	6	19	7	108
Media	6	6	6	4	6	1	3	3	5	6	5	46
Di	87	97	98	43	91	25	36	44	61	88	57	727

Note: DirB3, Directorate General of Hazardous Waste Management; BKSDA, Natural Resources Conservation Agency; KPHP, KPHP Minas; PHR, Pertamina Hulu Rokan; NGO, non-governmental organization.

The substantial influence and dependence of government agencies emphasize the need for robust regulatory frameworks and inter-agency collaboration to implement sustainable remediation strategies effectively. The low influence and dependence of local communities raise concerns about their potential exclusion from decision-making processes. This necessitates proactive efforts to incorporate their knowledge and address their concerns, ensuring equitable participation in remediation and restoration activities.

The influence and dependency map between actors is a graphical representation of the positions of actors concerning their influence and dependency on each other (Figure 3). Each actor's position on the influence-dependence quadrant map consists of four quadrants: (1) influential actors (high influence and low dependency), (2) intermediate actors (high influence and high dependency), (3) dependent actors (low influence and high dependency), and (4) autonomous actors (low influence and low dependency). The primary purpose of actor mapping in Figure 3 is to determine the influence and dependency status of actors, identify which groups of actors influence and are influenced, which actors need to be involved, and what capacities need to be improved. Mapping also helps illustrate interests, potential conflicts or coalitions, and patterns of relationships between actors.

The roles of the oil and gas company (PHR), contractors, DirB3, BKSDA, and KPHPMinas are included as actors with strong influence and dependence on other actors, positioned in quadrant 2. Although this group of actors with high dependence has strong influence and great potential to contribute to the process of restoring oil-contaminated soil in TAHURA SSH, its position in the system tends to be unstable because it is vulnerable to being influenced by other actors (its performance depends on other actors).

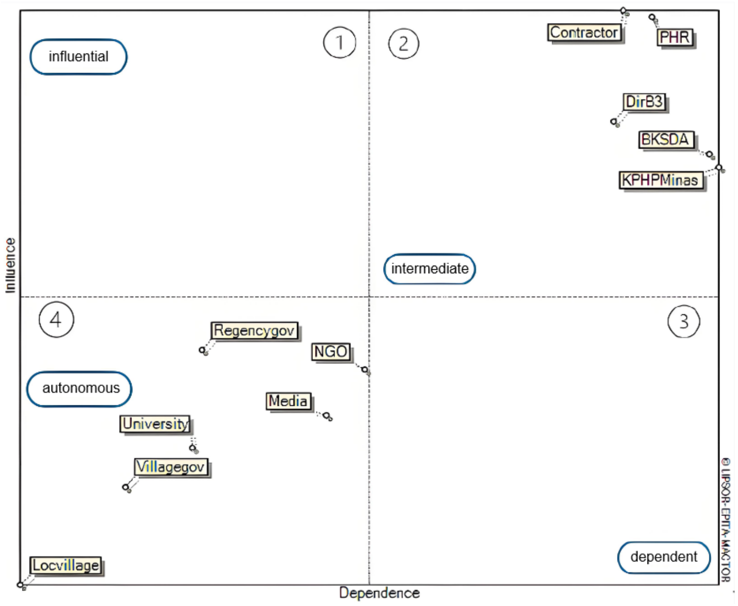

Figure 3. Influence and dependency map between actors

Restoring oil-contaminated soil in forest areas requires collaboration among oil companies, contractors, and regulators (DirB3, BKSDA, and KPHPMinas). Each party plays a role in ensuring effective environmental recovery and restoration.

Oil companies are primarily responsible for initial contamination and thus bear responsibility for funding and implementing remediation efforts [21]. Contractors are engaged in the technical aspects of soil remediation using various methods and technologies [22]. Regulators set guidelines and monitor compliance to ensure environmental safety [23]. Although the roles of oil companies, contractors, and regulators vary, their collaboration is essential for effective soil restoration. Each party must fulfil its responsibilities while working together to address the challenge of oil pollution in forest areas. This collaborative approach ensures compliance with environmental standards and encourages the development of innovative and sustainable remediation solutions.

Other actors in quadrant 4 include the regency government (Regencygov), village government (Villagegov), local community, universities/experts, non-governmental organizations (NGOs), and media. These actors have low influence and dependence on other actors. The actors in quadrant 4 are relatively passive and independent of the system.

The restoration of oil-contaminated land in forested areas involves collaboration among local governments, universities, NGOs, and the media. Local governments play an essential role by implementing environmental regulations, facilitating community involvement in recovery efforts, and prioritizing local needs and concerns [24]. Universities make significant contributions through research and development of innovative recovery technologies and practices that can improve the effectiveness of cleanup efforts [25].

Academic expertise often leads to the creation of sustainable solutions tailored to specific environmental challenges. NGOs are essential advocates of ecological justice, providing resources and support for community engagement in restoration initiatives [26]. Additionally, the media plays a vital role in raising public awareness of oil pollution issues, highlighting the importance of recovery efforts, and fostering community interest and involvement. The press can mobilize community actions and support recovery projects. The participation of local communities is critical to the success and sustainability of recovery efforts, as they possess traditional ecological knowledge and have a vested interest in maintaining environmental health [27]. The integration of local communities in the recovery process increases the effectiveness of these efforts and empowers communities economically and socially [28]. Although the actor role mapping results place them in quadrant 4, the successful recovery of oil-contaminated land in forest areas depends on the synergistic efforts of local governments, universities, NGOs, and the media, each contributing unique strengths to address environmental challenges effectively.

3.2 Actor's Implications for the Goals

The histogram (Figure 4) visually represents the level of agreement or disagreement among stakeholders regarding various goals associated with sustainable remediation. The goals are listed vertically, and the horizontal bars indicate the degree of agreement or disagreement.

Based on the factor histogram analysis, several key goals for remediation showed strong stakeholder agreement. Ecosystem restoration was the most widely agreed-upon objective, with the highest factor deal score of 26. This indicates strong consensus among stakeholders that restoring forest ecosystems is a primary goal. Long-term sustainability, with a score of 25, was the second most agreed-upon objective. This result underscores the importance of developing enduring and viable solutions. Tied with long-term sustainability at a score of 25, minimizing environmental impact was also a widely supported goal. This strong agreement demonstrates a clear commitment to reducing the negative environmental consequences of remediation activities. Sustainable land use practices were recognized as an important and agreed-upon remediation component, with a factor deal score of 20. Finally, protecting public health was also a widely accepted goal, as evidenced by its factor deal score of 19.

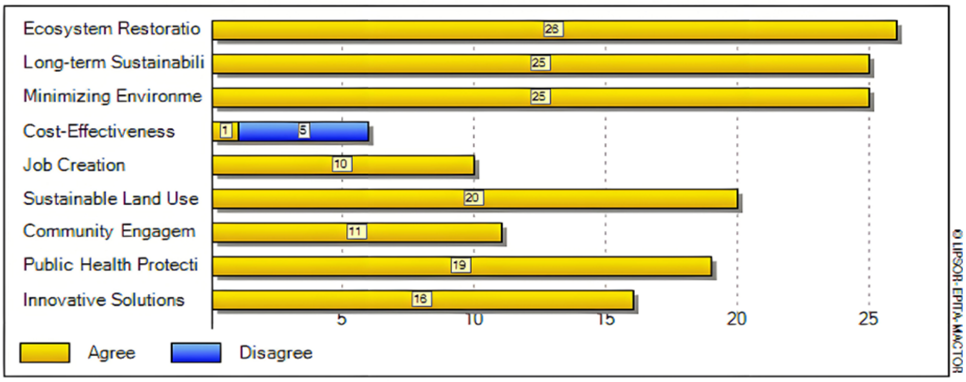

Figure 4. Histogram of actors' implications for their goals

Histogram analysis reveals significant disagreement regarding the cost effectiveness goal. With a distribution of one on the "Agree" side and five on the "Disagree" side, the data indicates a substantial divergence of opinion among stakeholders. This disparity suggests that there is no consensus on whether this objective is being successfully met or adequately prioritized. Disagreements over the cost effectiveness of forest soil remediation stem from the difficulty of monetizing long-term ecological benefits and the complexity of site-specific costs and benefits, often involving conflicting objectives and stakeholders [29]. The high cost of remediating contaminated soil in forest areas is a source of significant disagreement due to multiple complex factors. Unlike urban or agricultural land, a forest's value is not easily quantified, leading to differing economic and ecological valuations [30].

Restoration of oil-contaminated soils in forest areas presents unique challenges, wherein cost variables play a crucial role in determining the effectiveness and feasibility of different recovery strategies [31]. The choice of technology [32] is a primary factor influencing recovery costs. Various recovery technologies, both in situ and ex situ, are available, each with different cost implications. In situ methods, which treat contaminated soil on site, tend to be more cost-effective because of reduced excavation and transportation costs [33]. However, these methods may face challenges in effectively delivering and mixing necessary amendments with contaminants. In contrast, ex situ methods, such as thermal desorption, involve excavating contaminated soil for treatment, which can be costly and disruptive but allows for greater process control and potentially faster recovery [34, 35]. Setting remediation goals is another important aspect that affects cost. Recent developments in chemical-specific soil cleanup guidelines using a risk-based approach can provide customized and potentially cost-effective remediation strategies. These guidelines can assist in setting realistic cleanup targets aligned with site-specific conditions [36] and optimizing resource use.

The convergence graph (Figure 5) provides a valuable snapshot of stakeholder relationships and potential alliances. It highlights the central role of PHR, the potential for coalitions, and areas of potential conflict. By further analyzing the MACTOR data and understanding the specific context, we can better understand the dynamics and possible outcomes of this situation.

The provided actor analysis reveals distinct patterns of convergence and divergence among stakeholders. The strongest alignment is observed between the PHR and the contractor, with a score of 22 indicating a deep-seated collaboration focused on project execution and resource management. Other significant convergences, highlighting strong alliances, include the PHR with the Regencygov (17.5), BKSDA (18.5), and KPHP Minas (20.8), as well as a key partnership between KPHP Minas and BKSDA (17). These strong connections suggest a framework of shared interests and objectives. In contrast, moderate convergences, such as those between the Regencygov and NGOs (11.5) and the university and contractor (11), point to areas of potential cooperation but with less intense alignment. The analysis also highlights areas of weak convergence, particularly the limited connections between the local community and other stakeholders, suggesting a potential lack of shared interests or a framework for collaboration. This distribution underscores a complex network of relationships, with some actors closely aligned while others operate with minimal shared objectives.

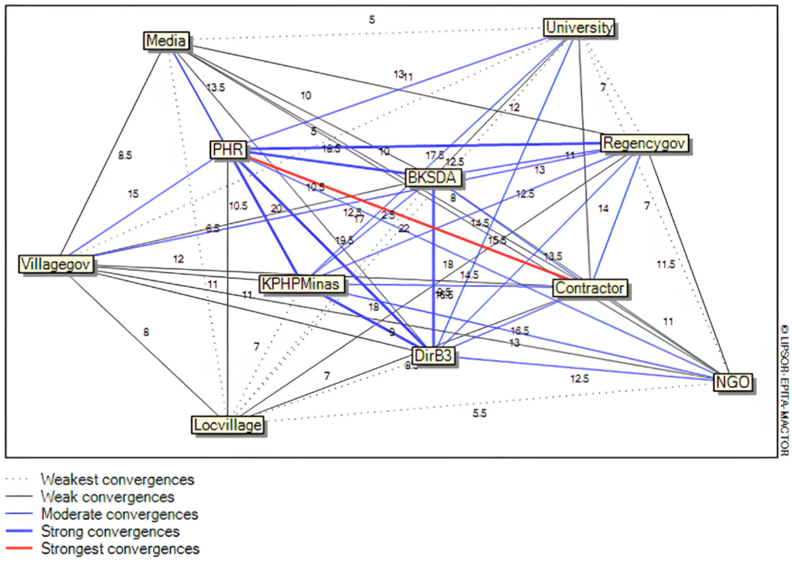

Figure 5. Convergence between actors

The analysis of stakeholder convergence within the KPHP Minas reveals several key strategic insights. The PHR emerges as a central and highly influential actor, evidenced by its numerous and strong convergences with other stakeholders, suggesting that it holds significant sway over project resources and activities. This strong alignment also indicates the potential for powerful coalitions to form, particularly among the PHR, contractor, BKSDA, and Regencygov, which could collectively shape project outcomes. In contrast, weak convergences—notably, the limited connections between the local community and other parties—highlight a potential for conflict, suggesting that local interests may be overlooked. However, some convergences point to constructive collaboration, such as the strong alignment between the NGO and BKSDA on conservation issues and the partnership between the university and contractor on technical or research-related projects. This complex web of relationships indicates that while some actors are closely aligned, others operate with minimal shared interests, requiring a nuanced approach to management and cooperation.

The MDII matrix and influence and dependence map highlight the PHR (likely a resource utilization company) and the contractor as central actors with high influence and dependence. This underscores their crucial role in driving the remediation process and their responsibility for prioritizing sustainable practices. Their decisions regarding remediation techniques, site management, and community engagement significantly impact sustainability outcomes.

Government agencies, including the DirB3, BKSDA, and KPHP Minas, also exert strong influence and dependence. This emphasizes their regulatory and oversight roles and the need for effective collaboration among them to ensure the implementation of sustainable remediation strategies. The analysis suggests that successful remediation requires strong partnerships between these agencies and the private sector (PHR and contractors). A recurring concern across analyses is the potential marginalization of local communities (Villagegov and Locvillager). Local communities are marginalized in forest hydrocarbon remediation by being excluded from decision-making, lacking information sharing, and having insufficient engagement in the process. To enhance participation, methods include early and continuous engagement, providing transparent information in local languages, offering capacity-building and training, ensuring cultural appropriateness of remediation techniques, involving local knowledge, establishing benefit-sharing mechanisms, and creating formal platforms for community input and collaboration [37]. Their low influence and dependence, as indicated in the MDII matrix and influence and dependence map, highlight the risk of their voices being overlooked in decision-making processes. The histogram also shows moderate agreement on community engagement, suggesting that while considered necessary, it might not be prioritized as highly as other goals. This necessitates proactive efforts to ensure meaningful participation and address concerns.

The histogram reveals strong agreement among stakeholders on prioritizing ecological goals, such as ecosystem restoration, long-term sustainability, and minimizing environmental impact. This indicates a shared commitment to environmental protection and recovery. However, significant disagreement on cost effectiveness suggests potential conflicts or trade-offs between economic and ecological considerations. Overall, the analysis emphasizes the need for an integrated and inclusive approach to remediation. This includes fostering collaboration to establish strong partnerships among the private sector, government agencies, and local communities; ensuring equity by guaranteeing the equitable participation of all stakeholders, particularly local communities, in decision-making processes; balancing ecological goals with economic considerations and social impacts; and encouraging innovation by adopting innovative and sustainable remediation technologies.

3.3 Integration of Matrix of Alliances and Conflicts: Tactics, Objectives, and Recommendations Results with the Pentahelix Approach in Soil Remediation Context

Identifying stakeholder roles and interaction patterns in remediating oil-contaminated soil in forest areas is a multidimensional issue that requires a deep understanding of actor dynamics. By adopting the pentahelix framework, which includes government, business, academia, community, and media elements, and integrating it with the findings of MACTOR analysis, we can obtain a comprehensive picture of the complexity and potential for collaboration in the remediation process.

The MACTOR analysis revealed two main categories of actors based on their influence and dependence: actors with high influence and high dependence, and those with low influence and low dependence. Understanding these two categories is essential for formulating effective collaborative strategies.

The group of actors with high influence and dependency (Quadrant 2) serves as the primary driver of the remediation process. Their decisions directly shape the direction and success of contamination management efforts. MACTOR identifies PHR, the implementing contractor, DirB3, BKSDA, and KPHP Minas as key actors in this category.

PHR and the contractor play central roles within the business pillar. As the business entity responsible for contamination, PHR dominates financial and technical resource allocation for remediation projects. The operational success of the contractor, which technically implements remediation, is highly dependent on the commitment and funding from PHR. Both are intrinsically interdependent on the regulatory and licensing frameworks issued by the government and community social support.

Meanwhile, from the government pillar, three actors had high influence and interdependence: the Directorate General of PSLB3, BKSDA, and KPHP Minas. The Directorate General of PSLB3 acts as the highest regulator, and its policies and law enforcement directly influence PHR and contractor obligations. As direct managers of forest areas, the BKSDA and KPHP Minas significantly influence operational permits and environmental compliance monitoring in the field. The mutual dependencies among these government actors and with the business pillar's compliance highlight the urgency of vertical and horizontal synergy and coordination among government agencies. Without this harmonization, remediation processes may be hindered by conflicts of authority or differing priorities.

Although the MACTOR analysis shows that the Regencygov, Villagegov, Locvillager, higher education/experts (Academia), NGOs, and mass media have relatively low influence on core remediation decisions and are not overly dependent on this project for their continued functioning, their roles within the pentahelix framework (Figure 6) remain fundamental to ensuring the legitimacy, accountability, and social sustainability of the project.

From the government pillar, the Regencygov and Villagegov serve as local facilitators and liaisons between central/provincial policies and site-level realities. Although not directly involved in hazardous waste regulation, they are essential for building community acceptance, facilitating access, and mitigating potential social conflicts.

The community pillar, represented by local communities and CSOs, is the party most directly affected by contamination. Although their formal influence is low, their voices are crucial for providing input, conducting bottom-up oversight, and determining project social legitimacy. Rejection or distrust from the community can pose significant obstacles to remediation operations.

NGOs often act as independent advocates that amplify community voices and push for accountability from high-level actors. The Academia pillar, through universities and experts, provides a scientific basis for innovation. They can provide independent technical assessments, develop efficient remediation methods, and train human resources. Although their recommendations are advisory, these scientific contributions are vital to ensuring that implemented solutions are optimal and evidence-based. Finally, the mass media pillar is essential for disseminating information, shaping public opinion, and promoting transparency. By highlighting issues related to remediation, the media can raise public awareness, exert pressure on key actors, and ensure accountability.

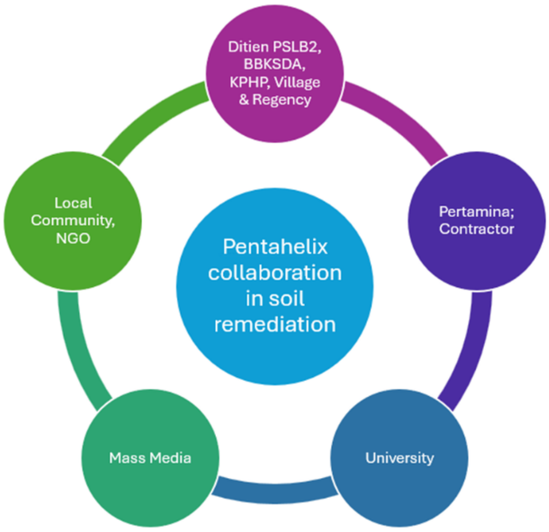

Figure 6. Pentahelix collaboration

Restoration of oil-contaminated land in forested areas involves collaboration among local governments, universities, NGOs, and the media. Local governments play an essential role by implementing environmental regulations, facilitating community involvement in restoration efforts, and prioritizing local needs and issues [27]. Universities make significant contributions through research and development of innovative restoration technologies and practices, which can enhance cleanup effectiveness [28]. Academic expertise often leads to the creation of sustainable solutions tailored to specific environmental challenges. NGOs are essential advocates of environmental justice, providing resources and support for community involvement in restoration initiatives [29]. Additionally, the media plays a vital role in raising public awareness of oil pollution issues, highlighting the importance of restoration efforts, and fostering public interest and involvement. The media can mobilize community actions and support restoration projects [38]. Local community involvement is essential to the success and sustainability of restoration efforts, as they possess traditional ecological knowledge and maintain the health of the environment. Integrating local communities into the restoration process enhances the effectiveness of these efforts and empowers communities both economically and socially. Although mapping results place these actors' roles in quadrant 4, the success of oil-contaminated land restoration in forest areas depends on the synergistic efforts of local governments, universities, NGOs, and the media, each contributing unique strengths to effectively address environmental challenges.

4 Conclusions

Sustainable remediation in TAHURA SSH requires more than technical success; it demands a shift toward inclusive governance. This study demonstrates that while government and industry lead the process, the exclusion of local stakeholders creates a risk of social friction and project failure. We recommend implementing a Pentahelix Collaboration Model that empowers local communities through education and direct participation in monitoring. Future policies should prioritize "nature-based solutions" that preserve the rainforest's microbial integrity while restoring its economic value to the surrounding population.

Author Contributions

Conceptualization, A.L.; methodology, A.L.; software, A.L.; investigation, A.L.; writing—review & editing, A.L., B., S., and E.; supervision, B. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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Nomenclature

DirB3	Directorate of Hazardous Waste
BKSDA	Natural Resources Conservation Center
KPHP	Production Forest Management Unit
PHR	Pertamina Hulu Rokan