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Valuing Ecological Recovery: An Environmental Economic Assessment of Oil-Contaminated Soil Remediation in Tropical Rainforests

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ABSTRACT

The hydrocarbon contamination affects approximately 5.9 ha of soil in Sultan Syarif Hasyim Grand Forest Park (Tahura SSH), a tropical rainforest in Riau Province, Indonesia. This study aims to determine the costs required to rehabilitate petroleum-contaminated soil and evaluate the economic significance of ecological restoration in a 5.9 ha area designated in Tahura SSH. This study provides a novel economic framework for assessing ecological damage and guiding recovery in a hydrocarbon-impacted area, integrating the Replacement Cost Method (RCM) through restoration cost calculations and the Resource Equivalence Analysis (REA) to assess and compensate for environmental damage-related losses. The study results show that the three main remediation technologies selected, bioventing, bioaugmentation & biostimulation, and ex-situ landfarming, were used to remediate oil-contaminated soil in Tahura SSH. The highest remediation costs are ex-situ landfarming, followed by bioaugmentation and biostimulation, and then bioventing. The ex-situ land farming method incurred the highest remediation costs. Nevertheless, it causes ecological harm in the SSH Tahura Area. REA determined that the area required to replace oil-contaminated land should be twice the baseline from 5.9 ha to 12.8 ha. Furthermore, the compensation paid by REA for environmental damage exceeded the initial assessment by 116.1% compared to using the Replacement Cost Method (Bioaugmentation & Biostimulation, Bioventing, and Ex-Situ Landfarming). This study offers stakeholders guidance on determining a fair environmental value for oil-contaminated soil. Future studies should evaluate additional ecosystem services in the Tahura SSH area for economic valuation.

Introduction

The health of ecosystems relies heavily on tropical rainforests, which are, unfortunately, disappearing at a fast pace. In the period from 2001 to 2020, 1.48 million square kilometers of tropical forests were wiped out, exceeding the overall land area of France, Spain, and Germany [1]. Deforestation markedly impacts climate change, contributing 6–17% of anthropogenic greenhouse gas emissions, primarily from humid tropical areas. [2]. Oil pollution significantly threatens tropical rainforest biodiversity, particularly in Sultan Syarif Hasyim Grand Forest Park, Riau Province, where six contaminated sites covering about 5.9 ha have been identified. Although the origin of the crude oil discharge is uncertain, there may be a connection to surrounding petroleum-related activities (PT. XYZ), with water likely aiding contamination in forest ecosystems. The impact of oil pollution on land and vegetation is significantly detrimental in rainforest ecosystems. It has an influence on soil characteristics, cuts down on porosity, and sets off anaerobiosis [3], which adversely affect the growth of plants [4,5]. Furthermore, hydrocarbons negatively impact plant biodiversity and hinder photosynthesis and seed processes [6,7].

The initiatives executed by PT. XYZ from 2022 to 2024 encompass the development of a Long-Term Management Plan for Tahura SHH, the demarcation of block areas, the performance of biodiversity

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assessments, and the appraisal of ecosystem restoration strategies. These efforts highlight an essential responsibility to rejuvenate environments spoiled by oil-related damage. It is essential to align sustainable remediation principles with applicable laws to rehabilitate contaminated land. Furthermore, The government has established a restoration framework for contaminated lands, as outlined in the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number P.101/MENLHK/SETJEN/KUM.1/11/2008, regarding Guidelines for the Restoration of Land Contaminated by Hazardous and Toxic Waste. This regulation specifies the sequential stages of remediation. It delivers stakeholders advice on numerous dimensions of contamination and decontamination. The regulation will function as a framework for the Environmental Function Restoration Plan.

To avoid environmental damage caused by oil pollution, many measures have been taken to clean up oil on the soil surface, including bioventing, bioaugmentation [8], biostimulation [9], and ex-situ landfarming [10]. The conflict between environmental restoration and financial expenditure is due to the intrinsic high costs of remediation efforts. The financial burden may impede essential actions, resulting in a conflict between economic feasibility and environmental accountability. This engenders a dilemma for stakeholders to weigh remediation costs against environmental benefits, further complicated by the hidden aspects of remediation and cost unpredictability [11]. Resource Equivalency Analysis (REA) is an essential methodology for evaluating environmental enhancements and associated expenses by measuring environmental alterations through defined, non-financial indicators to quantify resource fluctuations. Unlike Value Equivalency Analysis, REA offers a comparative framework for understanding biophysical trade-offs in environmental policies, facilitating a cost-effective approach to environmental compensation that targets specific resource changes [12].

Current cost-benefit analyses inadequately assess the economic implications of ongoing ecological service degradation during and post-clean-up efforts. Pure cost assessments neglect natural resource damage liabilities, resulting in ineffective management choices. This research tackles this issue by introducing and implementing a new integrated replacement cost method-resource equivalency analysis framework. This framework transcends basic engineering expenses, integrating cost assessment with ecological value by converting complex ecological harm (measured in DSAYs) into a quantifiable monetary liability, thereby offering a comprehensive evaluation of overall project costs.

This research aimed to assess the costs associated with rehabilitating petroleum-contaminated soil and analyze the economic importance of ecological restoration in a specified 5.9 ha area in Tahura SSH. Quantifying financial metrics emphasizes the economic importance of ecological restoration and supports informed investment in remediation. This study examines 5.9 ha of hydrocarbon-affected soil in Tahura SSH, Riau Province, intending to provide a localized economic assessment to enhance conservation efforts in the region.

Materials and Methods

Study Area

This study examined a 5.9 ha hydrocarbon-contaminated region within the Sultan Syarif Hasyim Grand Forest Park in Riau Province, Indonesia (Figure 1). This geographical area is distinguished by its rich biodiversity of tropical rainforests, complex edaphic conditions, and particular climatic characteristics, including heightened thermal levels and substantial precipitation. The soil, characterized by its sandy texture, showed a moisture level at 6.1%, registered a pH of 5.89, and recorded a temperature of 25.71°C. These parameters crucially influence contamination dynamics and remediation effectiveness in the region.

Valuation Framework

Replacement Cost Method

The Replacement Cost Method evaluates environmental degradation by estimating restoration or replacement costs for damaged natural resources or their services [13]. This methodological approach assesses the financial expenditures linked to the implementation of remediation technologies aimed at rehabilitating oil-contaminated soil to an established ecological standard, providing a measurable quantification of the financial resources necessitated for environmental restoration, which facilitates the evaluation of intervention expenses and can be integratively utilized alongside other valuation methodologies for a comprehensive economic assessment [14]. The Remediation Cost embodies the essential implementation of the Replacement Cost Method (RCM) within the domain of environmental engineering, systematically assessing the direct financial outlay necessary to rehabilitate a contaminated location physically. Computed as the Net Present Value (NPV) encompassing all capital expenditures, operational costs, and closure expenses throughout the comprehensive duration of active remediation, this standardized financial metric establishes a framework for evaluating the efficiency of various technological alternatives. This calculation incorporates initial capital investments (e.g., well installation for in situ remediation techniques such as bioventing or excavation for ex situ landfarming), ongoing operational expenditures (e.g., energy consumption, amendments, labor), and terminal site demobilization and closure costs. It is imperative to ascertain the financial valuation for each suggested remediation intervention utilizing a uniform social discount rate, thus creating a credible financial benchmark for the ultimate cost-effectiveness evaluation.

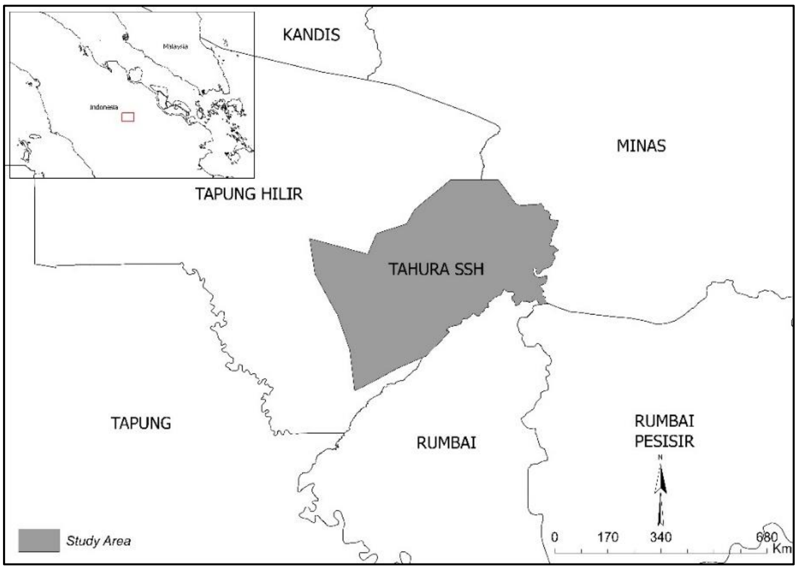

Figure 1. The research site where hydrocarbon-contaminated soil was discovered has been documented. Indicative zones of soil pollution have been delineated at the subsequent six locales: Minas 7B-89B, Minas 8B-48 PLG, Minas 8B-48 JP, Minas Tahura 8C-83, Minas 8C-96, and Muara Estuari.

Resources Equivalency Analysis

Resource Equivalency Analysis (REA) constitutes a service-to-service scaling methodology employed to evaluate the requisite restoration measures needed to compensate for the damage inflicted on natural resources. It underscores the parity of forfeited services with those acquired via compensatory restoration strategies instead of depending on traditional economic assessment methodologies [15]. Three principal phases are requisite in the execution of the REA analysis: 1) the computation of the debit amount, 2) the computation of the credit amount, and 3) the assessment of the scale and financial implications of restoration. The phases and elements that necessitate examination are depicted in Figure 2.

As illustrated in Figure 2, during the preliminary phase of quantifying the debit, it is imperative to obtain data regarding the specific category of habitat or natural resource that has sustained damage, as well as the extent of that damage. For instance, the proportional reduction in service. At this juncture, it is imperative to acquire information regarding the projected duration of the damage and the metric to be employed (hectares). After the completion of the debit phase, the subsequent phase of credit calculation commences, which entails the evaluation of restoration initiatives necessary to rehabilitate natural resources. This identification may be realized through restorative scenarios, including but not limited to revegetation or analogous endeavors. The total present value of the debt is calculated using the following formula:

$$PVD = \sum_{t=0}^{T} L_t (1 + r)^{P-t} \quad (1)$$

Where L_t is the interim loss amount, r is the discount rate, and P is the value at the time of the initial event (e.g., an oil spill).

The second stage is the calculation of credits, which also requires a scenario detailing the percentage of natural resources to be restored, the time needed for restoration, and the subsequent benefits. The present value of credits (PVC) is also calculated using a similar formula.

$$PVC = \sum_{t=0}^{T} S_t (1+r)^{P-t} \quad (2)$$

Where S_t is the service restored in period t (in percent for REA cases) from the restoration program.

The final stage of the REA calculation is to determine the scale or size of the restoration required after first calculating the discounted debit and credit. The scale of restoration, or the necessary amount of compensation, is obtained by dividing the debit by the credit.

$$S = \frac{\sum_{t=0}^{T} PVD_t}{\sum_{t=0}^{T} PVC_t} \quad (3)$$

Where PVD is the present value of debit, and PVC is the present value of credit, calculated using Equation (3).

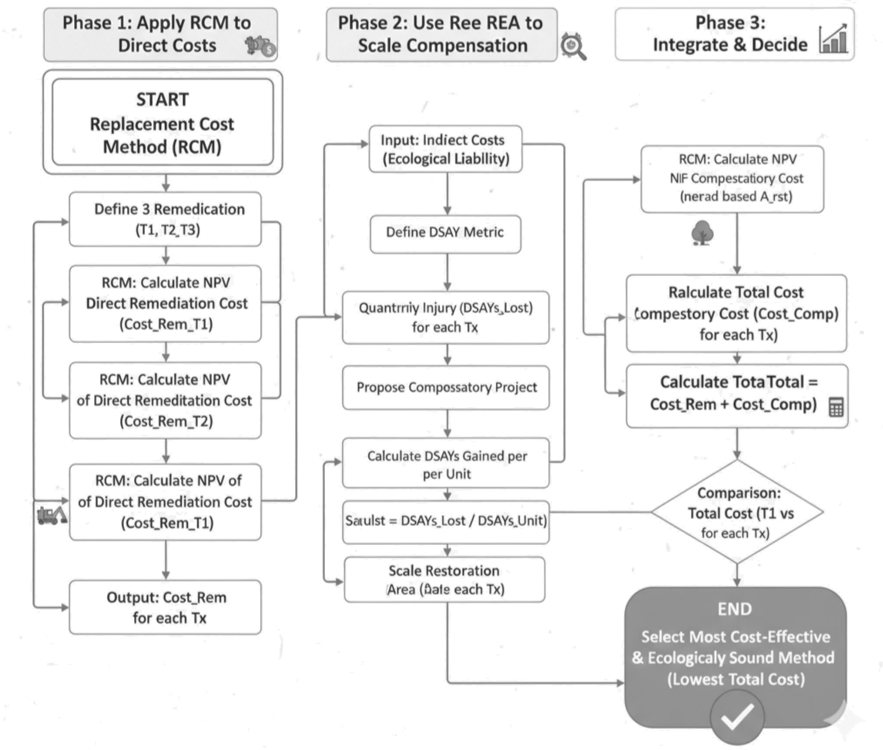

Figure 2. Step of integrated RCM and REA analysis. This flowchart illustrates a three-phase decision-making process for selecting the most cost-effective and ecologically sound environmental remediation method. It combines direct cost analysis (RCM), ecological compensation scaling (REA using DSAY metrics), and final integration to compare total costs across three remediation options (T1, T2, T3), guiding the selection of the optimal strategy.

All data were collected by calculating actual engineering and operational expenses, summing capital expenditures and operational costs (labor, energy, amendments), monitoring, and demobilization over the project life, and then discussing the data in focus group discussions and workshops involving experts and stakeholders (PT. XYZ) for the remediation of oil-contaminated soil. This research was conducted at the Sultan Syarif Hasyim Grand Forest Park (Tahura SSH) with an official permit. All data obtained from this research were approved for publication by KPHP Minas and the Government of Riau Province, as stated in the research permit/publication approval letter Number: 503/DPMPTSP/NON IZIN-RISET/68402 and 556/KPHP-MT/VIII/2024.

Results and Discussion

Results

General Condition of Sultan Syarif Hasyim Grand Forest Park

The Tahura SSH area, delineated by the inventory of prospective regions, epitomizes the tropical forest ecosystem of Sumatra, characterized predominantly by the Dipterocarpaceae family and serving as a critical habitat for Sumatran elephants. An examination of the topographical features, biological diversity, and arboreal ecosystems suggests that the Tahura SSH region possesses considerable prospects for ecotourism, educational initiatives concerning the environment, and academic inquiry. From a hydrochronological perspective, the Tahura SSH locality is located within the Siak watershed, which is instrumental in maintaining the stability of aquatic systems that directly support aquaculture ventures and the subsistence of surrounding communities [16]. Tahura SSH is situated at an elevation of approximately 100 meters above sea level, characterized by its undulating topography and the presence of red-yellow podzolic and alluvial soil classifications. In this conservation zone, six sites have been recognized as having hydrocarbon-contaminated soil, likely a consequence of historical petroleum extraction activities nearby. Through sampling conducted at three distinct locations, the concentration of Total Petroleum Hydrocarbons (TPH) within the soil at TTM sites was identified at depths varying from 0 to 30 cm, with values ranging from 21,500 mg/kg to 114,300 mg/kg (2.15% – 11.43%), and exhibiting a mean concentration of 70,467 mg/kg (7.05%) [17].

The Tahura SSH region is critically important as it serves as a habitat for the endemic Sumatran elephants (*Elephas maximus sumatrensis*) [18]. The residual forest cover in the Tahura SSH region is essential for biodiversity conservation, especially for the Dipterocarpaceae family and its ecosystems, thus promoting research, environmental education, and ecotourism, while also serving as a crucial catchment area for the Siak River, vital to local communities.

Cost of Remediating Hydrocarbon-Contaminated Soil in Tahura SSH

Several cost classifications presented in Table 1 exhibit consistency across the three remediation methodologies. The Project Management Team and the Survey & Detailed Engineering Design (DED) consistently allocate USD 179,878.00 and USD 48,727.00, respectively, irrespective of the selected approach. Similarly, the expenditures allocated for RPFLH and SSPLT, Construct and plug GWM (Groundwater Monitoring), Sampling and analysis, and Revegetation remained invariant, totalling USD 174,821.00, USD 139,206.00, USD 172,827.00, and USD 5,760.00, respectively, across all three methods.

The remediation costs differed significantly among the three methods evaluated. The Bioaugmentation and Biostimulation method required a total expenditure of USD 1,584,994.00, with the most significant portion allocated to soil remediation (USD 694,501.00). These three remediation methods are options for restoring oil-contaminated land in Tahura SSH in the future. The cost components listed in Table 1 are the costs required for the remediation of oil-contaminated soil in Tahura SSH.

Table 1. This table delineates a comprehensive financial analysis of three distinct soil remediation techniques: Bioaugmentation & Biostimulation (T1), Bioventing (T2), and Ex-situ Landfarming (T3). It compares expenses across key components like project management, engineering design, land preparation, remediation, and revegetationIt conducts a comparative analysis of expenditures across essential elements such as project administration, engineering design, land preparation, remediation efforts, and the process of revegetation. T3 shows the highest total cost, while T2 is the most economical overall.

Costs component	Remediation cost		
	Bioaugmentation & Biostimulation (T1) (USD)	Bioventing (T2) (USD)	Ex-situ Landfarming (T3) (USD)
Project Management Team (PMT)	179,879.00	179,879.00	179,879.00
Survey & Detail Engineering Design	48,727.00	48,727.00	48,727.00
Land preparation	169,273.00	-	169,273.00
Soil remediation	694,501.0 0	825,880.00	1,734,348.00
RPFLH & SSPLT	174,821.00	174,821.00	174,821.00
Construct & Plug GWM	139,206.00	139,206.00	139,206.00
Sampling & analysis	172,827.00	172,827.00	172,827.00
Revegetation	5,760.00	5,760.00	5,760.00
Total	1,584,994.00	1,547,100.00	2,624,841.00

The resource equivalency analysis (REA) for regions affected by oil contamination in Tahura SSH included a 15-year recovery scenario (Figure 3). This timeframe exceeds the 5-year recovery timeline stipulated in the prevailing Ecosystem Recovery Plan for the area, suggesting a more cautious and potentially more thorough methodology for evaluating environmental rehabilitation. The projected recovery duration for the Tahura region, attributed to oil contamination, is determined by a liability accord from the Ministry of the Environment, with the associated diagram illustrating the expected percentage of ecosystem-service recuperation over the forthcoming 15 years. The diagram illustrates the Year 1 baseline for residual service levels, indicating an initial value of roughly 55%. The diagram illustrates a consistent and gradual enhancement in service value, with the ecosystem service value projected to reach full restoration at 100% by Year 10, thereby signifying the total recovery of services to their original state, which was sustained at this 100% level through Year 14, encompassing the entire period of the study.

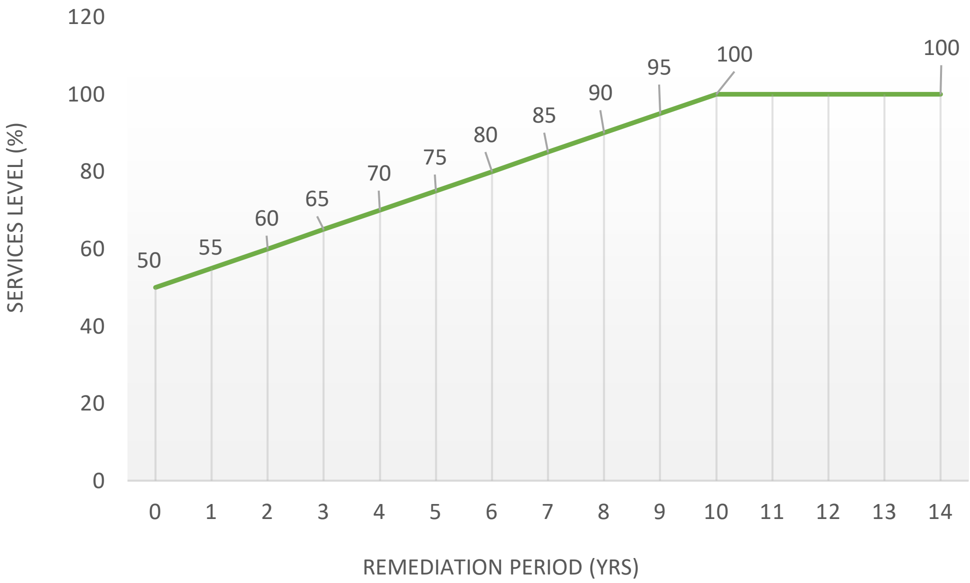

Figure 3. Graph of linear credit change. Valuation scenario using REA for oil contamination in Tahura SSH over 15 years.

Figure 3 depicts a decade-long evaluation of remediation initiatives from Year 0 to Year 9. This analysis presumes a stable damaged area of 5.9 hectares, indicative of the annual scope of necessary remediation efforts. To appropriately account for the time value of money, an annual discount factor of 3% was utilized. This application indicates that the future remediation efforts and costs are perceived as less significant when discounted to their present value. As a result, the discount factor exhibits a consistent decline throughout the duration, diminishing from a value of 1 in year 0 to 0.76 by the conclusion of year 9. Consequently, the present worth of the compromised region experiences a consistent diminution, decreasing from 5.90 hectares in Year 0 to 4.49 hectares in Year 9. This noted decrease signifies the diminished present worth of forthcoming remediation initiatives, rendering it an essential factor for strategic long-term planning and comprehensive cost-benefit evaluations of environmental restoration endeavors.

The aggregate Present Value (PV) attributable to the degraded area over a decade totalled 51.64 (Table 2), designated as the Σ Discounted PV Services Ha Years, which encapsulates the economic assessment of environmental services forfeited due to degradation, adjusted for a discount rate of 3%, and constitutes a critical component in the evaluation of natural resource impairment by illustrating the persistent economic consequences of environmental deterioration in contemporary contexts. Based on the literature, we used a 3% discount rate [15,19,20]. The primary rationale is that an elevated rate would significantly diminish the perceived value of prospective benefits and returns.

Table 2. Discounted debit calculation showed the total damage over time (debit) for each case. The Present Value damaged value in column 4 is the result of multiplying Damaged Ha by the Discount Factor.

Year	Damaged Ha	Discount Factor (@3%)	PV Damaged
0	5.9	1	5.90
1	5.9	0.97	5.72
2	5.9	0.94	5.55
3	5.9	0.91	5.38
4	5.9	0.89	5.22
5	5.9	0.86	5.07
6	5.9	0.83	4.91
7	5.9	0.81	4.77
8	5.9	0.78	4.62
9	5.9	0.76	4.49
∑ Discounted PV Services Ha Years			51.64 (a)

Table 3 delineates the discounted Present Value (PV) credit over a 15-year period, which is pivotal for evaluating the current worth of prospective environmental benefits. The timeline from Year 0 to Year 14 demonstrates the documentation and depreciation of environmental service improvements, with the service gain percentage increasing from 5% to a consistent 50% by Year 14, indicating a continuous improvement in ecological services. The diminishing discount factor of 1 to 0.65 evaluates the present value of future service gains, highlighting the critical importance of a calculated habitat size of 12.80 ha in ecological restoration and compensatory mitigation.

Table 3. Assessment of the discounted present value credit over a period of 15 years. Discounted present value is crucial in environmental valuation, assessing present worth of future environmental impacts via a discount rate.

Year	Service gain (%)	Discount Factor	PV Credit
0	5	1	0.05
1	10	0.97	0.10
2	15	0.94	0.14
3	20	0.91	0.18
4	25	0.89	0.22
5	30	0.86	0.26
6	35	0.83	0.29
7	40	0.81	0.32
8	45	0.78	0.35
9	50	0.76	0.38
10	50	0.74	0.37
11	50	0.72	0.36
12	50	0.69	0.35
13	50	0.67	0.34
14	50	0.65	0.33
∑ PV credit (DSHaYs) per Ha			4.03 (b)
Replacement habitat size (Ha) = a/b			12.80

The data in Table 4 highlight a significant divergence between traditional cost estimation and an ecological liability-inclusive valuation approach, fundamentally altering the economic framework of environmental remediation. The Replacement Cost Method (RCM) prior to Resource Equivalency Analysis (REA) yields an understated financial impact, demonstrated by Bioventing's preliminary valuation of USD 1,547,100.00. The incorporation of REA necessitates a clear economic assessment of ecosystem service temporal loss, converting the inevitable ecological "debt" from cleanup into a measurable financial obligation. A notable discovery is a 116.1% rise in total valuation for all bioremediation technologies, indicating that mandatory ecological compensation costs frequently surpass direct cleanup engineering expenses. This escalation elevates Bioventing's valuation to USD 3,343,309.32 and Ex-situ Landfarming's to over $5.6 million, highlighting a critical finding: neglecting the hidden costs of lost natural resource services renders environmental restoration economically infeasible. When normalized to a management unit, Ex-situ Landfarming presents the highest remediation cost at USD 961,411.17 per hectare post-REA integration. Bioaugmentation and Biostimulation follow at USD 580,542.19 per hectare. Bioventing incurs the lowest expense at USD 566,662.60 per hectare. The Cost Total metric offers decision-makers a quantifiable economic impact of choices, functioning as a critical accountability tool that mandates remediation strategies to incorporate the total financial responsibility of ecological restoration.

Table 4. Assessment of natural resources and ecological systems post-REA using three remediation methods. These methods were used in accordance with best practices implemented by oil and gas companies located in forest areas.

Valuation (USD)	Bioaugmentation & Biostimulation	Bioventing	Ex-situ Landfarming
Before REA Valuation (RCM)	1,584,994.00	1,547,100.00	2,624,841.00
After REA	3,425,198.90	3,343,309.32	5,672,325.89
% increase in the value of natural resources	116.1%	116.1%	116.1%
Remediation cost (USD, Ha-1) (After REA)	580,542.19	566,662.60	961,411.17

Discussion

The occurrence of petroleum leaks in the Tahura SSH region constitutes a grave issue, as substantiated by Total Petroleum Hydrocarbon (TPH) assessments, which signify considerable pollution. This necessitates prompt rehabilitation endeavors to avert additional ecological degradation. Government Regulation No. 22 of 2021, concerning the implementation of environmental protection and management, requires business actors to restore environmental functions [21]. This assessment is vital for determining the most suitable restorative approach that reconciles ecological advantages and financial viability in the Tahura SSH region. Although the emphasis is frequently on expenditure and efficacy, the selection of rectification technique also relies on the particular circumstances of the location, legislative stipulations, and enduring viability [22–24]. Three rectification techniques are appropriate for the prevailing circumstances at Tahura SSH, predicated on the optimal methodologies implemented by PT. XYZ. Several methods for recovering oil-contaminated soil encompass bioaugmentation and biostimulation (in situ) [25], bioventing [26], and ex-situ landfarming [10]. The choice of these three techniques was congruent with the directives delineated in the Ecosystem Rehabilitation Strategy (ERS) for Tahura SSH for 2024–2028. The rectification expense assessment determined that the utmost expenditure was sustained by ex-situ landfarming, in situ bioremediation (bioaugmentation and biostimulation), and bioventing. The determination of corrective measures for petroleum-impacted soil in Tahura SSH must consider site-dependent circumstances, legislative structures, and sustainable methodologies while emphasizing techniques that reduce ecological disturbance to the forest biome. With respect to the environmental detriment induced by land-clearing methodologies, ex-situ landfarming occupies the foremost position, succeeded by bioaugmentation and biostimulation, and bioventing [27]. The ultimate selection of rectification technique will be ascertained by consensus among all parties involved.

The information delineated in Table 4 elucidates a significant incongruity between traditional cost assessment and a valuation methodology that integrates genuine ecological responsibility, fundamentally altering the economic computation of environmental restoration. When evaluated exclusively via the Replacement Cost Method (RCM), the fiscal repercussions seem deceptively minimal, as demonstrated by Bioventing's preliminary appraisal of USD 1,547,100.00. Nevertheless, the incorporation of the Resource Equivalency Analysis (REA) necessitates a definitive economic reckoning of the temporal diminution of ecosystem services, transmuting the inescapable ecological "obligation" accrued during and subsequent to remediation into a measurable fiscal responsibility. The substitution expenditure methodology possesses constraints in appraising ecological detriment resulting from petroleum leaks, as it predominantly emphasizes the expenditure associated with rehabilitating the terrestrial substrate (e.g., excavation and substitution) and neglects to encompass the intrinsic or ecological worth of the tainted milieu [28]. This approach does not consider diminished ecosystem services, such as biological diversity, natural resource functionalities, or the aesthetic and cultural significance of the impacted region, which are frequently incommensurable or challenging to attribute a financial worth [29,30]. The considerable fiscal encumbrance of ecological rehabilitation often presents considerable obstacles that may obstruct the execution of imperative restoration programs [31]. This quandary is exacerbated by the necessity to harmonize environmental advantages with economic limitations, frequently necessitating the formulation of inventive approaches to enhance resource distribution. Numerous methodologies have been examined to alleviate these expenditures, such as embracing fiscal portfolio administration and budgetary enhancement techniques [32]. These constraints impede efficient remediation, requiring innovative approaches to reconcile costs with environmental restoration aims [33]. Budgetary constraints present significant challenges; nonetheless, innovative and economical solutions may mitigate these financial issues, although their effectiveness is contingent upon localized conditions and varying initial contamination levels [34]. The challenge in evaluating environmental services for oil-contaminated land restoration stems from the complexity of monetizing enduring environmental benefits relative to the immediate measurable costs of remediation methods [35]. Conventional economic methodologies contend to encapsulate the inherent value of ecological detriment, ecosystem services, and the expenses associated with prospective deterioration, engendering a divergence between financial viability and ecological imperative, which constitutes a considerable obstacle for efficacious land stewardship and policy execution [36,37]. Financial limitations represent a significant obstacle to the rehabilitation of oil-contaminated locations, especially in emerging countries that have not emphasized the resolution of tainted terrain [38].

To mitigate undervaluation and challenges in the appraisal of Natural Resources and the Environment, additional assessment employs the resource equivalency analysis (REA) technique [39]. This approach can augment other economic assessment methodologies [19]. The expanse of territory afflicted by petroleum, initially quantified at 5.9 hectares in accordance with the Resources Equivalency Analysis (REA), augmented to 12.75 hectares. This indicates that the rehabilitation of 12.75 hectares recuperated in the tenth annum adequately compensated for the depletion of 5.9 hectares of compromised terrain. The unit valuation of contaminated land within the context of the Resources Equivalency Analysis (REA) escalates when the prospects for prospective utilization and economic advantage are acknowledged through site restoration, culminating in an elevated ecosystem service appraisal, and when the enhancement of the site's economic, social, and ecological significances subsequent to remediation is incorporated into the evaluation [40]. Other determinants that augment this unit valuation encompass the establishment of robust legal and policy infrastructures that promote remediation and the utilization of information to enhance superior risk management decision-making, consequently diminishing market hesitance and amplifying profitability [41].

The REA analysis also indicated a 116.1% augmentation in the worth of natural resources. The most salient discovery is a 116.1% increment in the aggregate valuation across all three bioremediation technologies, illustrating that the expense of obligatory ecological compensation frequently surpasses the direct engineering expenditures of remediation. This escalation propels Bioventing's total valuation to USD 3,343,309.32 and Ex-situ Landfarming's to over USD 5.6 million. Crucially, when normalized to a site management unit, the remediation cost per hectare (USD, Ha-1) reveals Ex-situ Landfarming to be the most costly cleanup alternative at USD 961,411.17 per hectare (predicated on the actual contamination area of 5.9 ha) subsequent to REA integration, followed by Bioaugmentation and Biostimulation at USD 580,542.19 per hectare, and bioventing at the minimal cost of USD 566,662.60 per hectare. The resultant Cost Total metric furnishes the decision-maker with the tangible economic implications of each alternative, functioning as an essential mechanism for accountability that guarantees that remediation strategies internalize the full financial encumbrance of ecological restoration. Although environmental degradation in the Tahura SSH area cannot be swiftly reinstated, the increase in the current value percentage is deemed a justifiable form of compensation for the detriment in this locale. The fiscal assessment of petroleum-polluted terrain does not enhance the worth of ecological assets; rather, it measures their deterioration and diminished worth attributable to petroleum pollution [42]. The procedure elucidates the considerable fiscal detriments and diminished ecological services (such as hydrological purification and carbon capture) that petroleum contamination inflicts, underscoring the necessity for alleviation and preservation to restore these forfeited values and avert additional harm to the forest ecosystem [43,44]. This research depends on conventional expense frameworks and supplier estimates for the Remediation Expense element. Despite being lucid, these modeled expenses may diverge from the actualized costs of a complicated, site-specific field implementation, necessitating prudence when utilizing these definitive values in acquisition choices.

Environmental valuation is an essential instrument for directing administration, preservation, and restoration in the occurrence of an oil discharge in a forest. The ramifications are intricate, linking ecological degradation to financial expenditures and impacting policy determinations pertaining to legal accountability, rehabilitation, and mitigation [45]. In the Forest Governance and Preservation Policy context, the evaluation underscores the fiscal significance of robust forest ecosystems, endorsing sustainable forest governance (SFG) methodologies that incorporate economic, societal, and ecological factors [46]. Meanwhile, in Jurisprudence, Harm Evaluation furnishes essential proof and justification for judicial proceedings against culpable entities, facilitating the recuperation of assets for rehabilitation and recompense for impacted populations [47]. Assessment can quantify rectification efficacy in the context of rectification methodologies. Rectification Efficacy assessment can evaluate the ecological repercussions of rectification endeavors, supplying information on the degree to which pollution and related detriments have been mitigated, as evidenced in investigations that illustrate a reduction in ecological repercussions subsequent to rectification activities [48]. Assessment can also discern cost-efficient methodologies. By juxtaposing financial expenditures with the realized ecological advantages, assessment can steer the choice of restoration techniques (e.g., bioremediation) that are both efficacious and financially sustainable [49].

Conclusions

The principal conclusion of this investigation is the conclusive resolution of the essential quandary presented in the introduction: depending exclusively on traditional remediation expenditures results in a significant and intolerable underestimation of environmental impairment. Our comprehensive Replacement Cost Method–Resource Equivalency Analysis (RCM-REA) framework illustrates that the expense of ecological liability is not negligible but often surpasses the direct engineering decontamination costs, culminating in a consistent 116.1% augmentation in the aggregate project valuation across all three bioremediation approaches.

This inquiry presents persuasive quantitative substantiation that the REA paradigm constitutes an essential, non-negotiable instrument for guaranteeing appropriate accountability and ecologically significant recompense in fisheries governance. By converting the temporal diminishment of discounted ecosystem services (DSAYs) into a verifiable fiscal compensation cost, our framework compels decision-makers to internalize the comprehensive financial encumbrance of Natural Resource Damages. The particular revelation that Ex-situ Landfarming represents the costliest technique (total expenditure surpassing $5.6 million) and necessitates a compensatory area more than twice the original contamination unequivocally designates it as the least advantageous alternative from both an economic and ecological perspective.

The principal inference is that governance and enforcement frameworks must expeditiously transition from solely expenditure-based evaluations to service-oriented remuneration. Regulatory entities must embrace the DSAY metric to precisely evaluate accountability and mandate that compensatory restoration, which encompasses addressing the 116.1% escalation in natural resource worth, be financed as an obligatory aspect of the comprehensive remediation budget. To reinforce the revolutionary capacity of this paradigm, forthcoming investigations should concentrate on substituting expert elicitation with empirical and probabilistic data. To progress beyond the existing deterministic analysis, subsequent studies should utilize probabilistic modeling (e.g., Monte Carlo simulations) on all indeterminate parameters (including the discount rate and unit cost fluctuations) to derive statistically robust confidence intervals for the ultimate Cost Total, thereby augmenting the accuracy and dependability of regulatory valuation.

Author Contributions

ABD: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing; **BAH:** Writing - Review & Editing, Supervision; **SWD:** Writing - Review & Editing; **EFR:** Writing - Review & Editing.

AI Writing Statement

During the preparation of this work authors used GRAMMARLY in order to paraphrase and proofread the sentences. After using this service, the needed and take full responsibility for the content of the publication.

Conflicts of Interest

The authors declare no conflicts of interest.

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