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Managing Environmental Impacts of Peatland Degradation through Restoration-Based Economic Strategies and Science-Supported Monitoring in the Kampar Peninsula, Indonesia

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ABSTRACT

Tropical peatlands are globally important ecosystems because of their carbon-storage capacity, hydrological functions, and biodiversity value. Peatland degradation caused by drainage, land conversion, and recurrent fires nevertheless continues to generate major environmental impacts in Indonesia, including carbon emissions, peat subsidence, habitat loss, and fire vulnerability. This study examines how these impacts are addressed in the Kampar Peninsula, Riau, through an integrated framework combining restoration interventions, restoration-based livelihood strategies, and science-supported ecological monitoring. A qualitative case-study synthesis based exclusively on secondary data was conducted using peer-reviewed studies, Indonesian policy documents, and institutional restoration reports. The reviewed evidence documents substantial historical forest-cover loss and the implementation of large-scale protection, canal blocking, rewetting, native-species revegetation, biodiversity inventories, camera-trap surveys, remote sensing, and community livelihood programmes under the Riau Ecosystem Restoration (RER) initiative. These records demonstrate the scale and diversity of restoration activities and provide baseline ecological information, but they do not by themselves establish long-term ecological recovery. Accordingly, the study distinguishes implemented activities and documented observations from expected ecological effects. The findings indicate that restoration-based livelihood programmes may reduce pressure on peatland resources when they are sustained through community participation, while ecological surveys, camera traps, hydrological observations, and spatial monitoring can strengthen restoration accountability. Molecular monitoring tools such as environmental DNA (eDNA) and DNA barcoding, together with biological restoration applications such as tissue culture and microbial approaches, are treated as prospective directions requiring site-specific field validation rather than as established components of the Kampar case. The study contributes an evidence-informed preliminary conceptual model linking hydrological restoration, habitat protection, restoration-economy mechanisms, and science-supported monitoring while differentiating implementation evidence, observed conditions, expected effects, and verified ecological outcomes.

1. INTRODUCTION

Tropical peatlands are among the most critical ecosystems for global climate stability and environmental sustainability due to their unique capacity to accumulate and store carbon over long periods of time. Although peatlands occupy only a small proportion of the Earth's terrestrial surface, they contain a disproportionately large share of global soil carbon, functioning as one of the world's most important natural carbon sinks [1]. In addition to carbon sequestration, peatlands regulate hydrological cycles by retaining large volumes of water, mitigating floods, maintaining groundwater stability, and supporting complex ecological networks that sustain diverse flora and fauna communities. Consequently, peatland ecosystems play a central role in climate change mitigation, biodiversity conservation, and sustainable landscape management.

Despite their ecological importance, tropical peatlands in Southeast Asia, particularly in Indonesia, have experienced severe degradation due to unsustainable land use practices [2]. Peatland drainage, industrial logging, forest conversion into industrial timber plantations (HTI), and the rapid expansion of oil palm cultivation have significantly altered peat hydrology and accelerated peat oxidation. These pressures contribute to peat subsidence, loss of soil organic carbon, increasing vulnerability to drought, and recurring large-scale peat fires [3]. Such fires not only result in extensive biodiversity destruction and habitat fragmentation but also release massive quantities of greenhouse gases into the atmosphere, intensifying regional haze crises and undermining national climate commitments.

The degradation of peatland ecosystems generates a range of environmental impacts extending beyond local ecological damage. Peatland drainage and oxidation contribute

substantially to greenhouse-gas emissions, while land subsidence increases vulnerability to flooding and long-term ecosystem collapse. Recurrent peat fires further intensify carbon emissions, transboundary haze pollution, biodiversity loss, and public-health risks. Therefore, evaluating peatland conservation strategies requires not only an ecological perspective but also an environmental-impact perspective that considers hydrological change, carbon dynamics, fire risk, and socio-economic consequences associated with peatland degradation [2, 3].

The Kampar Peninsula, located in Riau Province, represents one of Indonesia's most significant peatland landscapes, characterized by deep peat deposits and extensive peat swamp forests [4]. The region is recognized for its high conservation value due to its large carbon stock potential and its role as a habitat for endangered wildlife [5], including the Sumatran tiger (*Panthera tigris sumatrae*) and various threatened bird species [6]. However, Kampar Peninsula has also become a hotspot of land use conflict and ecological degradation, primarily driven by drainage infrastructure development, plantation expansion, and forest exploitation [7]. Historical land cover records indicate substantial peat swamp forest loss [8], suggesting that conservation efforts must not only focus on protection but also address restoration needs at a landscape scale.

In response to widespread peatland degradation, ecosystem restoration has emerged as a key strategy for peatland conservation. Restoration interventions commonly include hydrological restoration through canal blocking and rewetting, revegetation through native species planting, biodiversity monitoring, and community-based fire prevention. In Indonesia, restoration has been increasingly institutionalized through government agencies such as the Peat and Mangrove Restoration Agency (BRGM) and regulatory frameworks aimed at protecting peat ecosystems [9]. However, restoration outcomes remain uneven, and challenges persist regarding governance, community participation, economic incentives, and the long-term sustainability of restoration projects.

Furthermore, recent discussions in conservation science emphasize that effective peatland protection requires integrated approaches that combine ecological restoration with socio-economic revitalization. Restoration-based economic approaches focus on ensuring that conservation generates tangible livelihood benefits for local communities through sustainable enterprises such as paludiculture, freshwater fisheries, eco-tourism, and environmentally friendly agriculture. Without such economic integration, restoration projects often face resistance, illegal encroachment, or recurring land clearing practices that undermine conservation gains.

In parallel, science-supported monitoring has gained increasing attention as a means of improving restoration assessment. In peatland landscapes, implemented monitoring commonly combines ecological inventories, camera traps, hydrological observations, remote sensing, and ground-truth validation. Biotechnology-based techniques such as environmental DNA (eDNA), DNA barcoding, tissue culture, and microbial restoration may complement these approaches, but their contribution should be evaluated separately and only where direct field application and outcome data are available.

Recent studies on tropical peatlands have provided important insights into peat hydrology restoration, land-use change dynamics, carbon emissions, biodiversity conservation, and peatland governance. Hydrological restoration studies have primarily examined canal blocking, rewetting effectiveness, groundwater-table recovery, and carbon-emission reduction mechanisms [3, 9, 10]. Other studies have focused on land-use change and governance challenges, including policy coherence, plantation expansion, and institutional management of peatland landscapes [2, 7]. Biodiversity-related studies have highlighted habitat conservation and species protection within tropical peat swamp forests [5, 6], while restoration initiatives have generally been evaluated from ecological or policy perspectives [9].

However, these research streams remain partly fragmented. Existing studies rarely integrate environmental impacts, restoration interventions, community livelihood strategies, and monitoring evidence within a single analytical framework. Consequently, limited attention has been given to how restoration programmes can address hydrological degradation, habitat loss, fire vulnerability, and socio-economic pressures while maintaining a transparent distinction between restoration activities, documented observations, and longer-term ecological effects.

Existing operational frameworks provide an important foundation for peatland restoration but serve somewhat different purposes from the analytical integration pursued in this study. In Indonesia, the BRGM 3R approach, Rewetting, Revegetation, and Revitalization, organizes restoration around hydrological recovery, vegetation rehabilitation, and socio-economic revitalization. Similarly, the Riau Ecosystem Restoration (RER) initiative applies a PARM model to guide landscape-level conservation and restoration management. These frameworks are primarily intervention- and management-oriented. The present study does not seek to replace either approach. Instead, it extends their logic analytically by connecting degradation pressures, ecological interventions, restoration-economy mechanisms, and scientific monitoring within an explicit evidence pathway. In particular, the proposed model differentiates implementation evidence, observed ecosystem conditions, expected effects, and verified outcomes, thereby addressing the risk of interpreting restoration activities themselves as evidence of ecological recovery. It also incorporates prospective molecular and biological tools as a future monitoring layer rather than treating them as already validated components of peatland restoration.

A further gap concerns the role of monitoring in integrated peatland governance. Most studies emphasize either biophysical restoration or institutional arrangements, while fewer studies explain how field surveys, camera traps, hydrological records, and spatial analysis can be combined with restoration-economy mechanisms. Biotechnology-based methods are increasingly relevant to conservation science, but in the Kampar Peninsula they are better understood as prospective options rather than established restoration practices documented by the available case evidence.

Therefore, this study examines peatland conservation in the Kampar Peninsula, Riau, through an integrated framework combining restoration interventions, restoration-based economic strategies, and science-supported monitoring. The guiding question is: How can documented restoration activities, community livelihood programmes, and ecological monitoring be integrated to strengthen environmental-impact governance in the Kampar Peninsula?

The objectives are: (1) to identify the principal degradation pressures and environmental impacts affecting the Kampar

Peninsula; (2) to document and assess the scale, purpose, and available evidence for restoration interventions and community-based restoration-economy programmes under the RER initiative; and (3) to develop an integrated framework that distinguishes implemented monitoring tools from prospective biotechnology applications and identifies the evidence needed to evaluate long-term restoration outcomes.

Accordingly, the contribution of this study lies not in proposing an alternative to established restoration frameworks, but in developing an evidence-informed preliminary conceptual model that connects their intervention logic with environmental-impact governance and evidence differentiation. The model makes four specific contributions. First, it links environmental pressures, ecological restoration, restoration-economy mechanisms, and scientific monitoring at the system level. Second, it explicitly incorporates livelihood and economic mechanisms as part of the pathway through which restoration pressures may be reduced. Third, it distinguishes implemented monitoring approaches from prospective molecular and biological tools that require site-specific validation. Fourth, and most importantly, it introduces evidence-type differentiation by separating implementation activities, observed environmental conditions, expected effects, and verified ecological outcomes. This distinction provides a more cautious basis for evaluating restoration claims and identifies where additional longitudinal or field-based evidence is required. Because the model is derived from a secondary-data synthesis of a single landscape, it is presented as a preliminary conceptual model requiring subsequent empirical validation rather than as a validated restoration framework.

2. LITERATURE REVIEW

2.1 Tropical peatland degradation and environmental impacts

Tropical peatlands are unique wetland ecosystems formed through the long-term accumulation of partially decomposed organic matter under waterlogged conditions [11, 12]. Although peatlands occupy only a small proportion of the global land surface, they store approximately one-third of the world's soil carbon and therefore play a critical role in climate regulation, biodiversity conservation, and hydrological stability [11]. Indonesia contains one of the largest tropical peatland areas globally, with approximately 13.4 million hectares of peatlands distributed across Sumatra, Kalimantan, and Papua [13].

However, peatland ecosystems have experienced extensive degradation due to drainage, logging, industrial timber plantations, agricultural expansion, and recurrent fires [2]. Drainage lowers groundwater levels and exposes peat to aerobic decomposition, accelerating carbon emissions and peat subsidence [3]. Land-use conversion fragments habitats and reduces biodiversity, while recurrent peat fires generate transboundary haze pollution, substantial greenhouse-gas emissions, and long-term ecological degradation [2].

From an environmental-impact perspective, peatland degradation produces four major consequences: (1) increased carbon emissions and loss of carbon-storage functions; (2) hydrological disruption through declining water tables and increased flood risk; (3) biodiversity loss caused by habitat fragmentation and ecosystem simplification; and (4) socio-economic impacts associated with fire disasters, land degradation, and declining ecosystem services [2, 3]. These impacts demonstrate that peatland conservation is not only a biodiversity issue but also a broader environmental governance challenge.

2.2 Restoration-based conservation

Ecological restoration has emerged as one of the most important approaches for addressing peatland degradation. The Society for Ecological Restoration defines restoration as the process of assisting the recovery of ecosystems that have been degraded, damaged, or destroyed [9]. In tropical peatlands, restoration seeks to restore ecological functions, improve hydrological stability, reduce carbon emissions, enhance biodiversity, and strengthen ecosystem resilience.

Peatland restoration generally consists of three interconnected components. First, hydrological restoration focuses on restoring natural water regimes through canal blocking, rewetting, and groundwater-level management [10]. Hydrological recovery is widely regarded as the foundation of successful peatland restoration because peat ecosystem functions depend heavily on maintaining high water tables.

Second, revegetation aims to restore vegetation cover and ecosystem structure through the planting of native peatland species such as ramin (*Gonystylus bancanus*), jelutung (*Dyera polyphylla*), and sago (*Metroxylon sagu*) [9]. Revegetation contributes to habitat recovery, biodiversity enhancement, and long-term ecosystem stability. Third, biodiversity protection and monitoring are implemented to evaluate restoration outcomes and ensure ecosystem recovery. These activities include species inventories, habitat assessments, ecological surveys, and long-term monitoring programmes [9]. Together, these restoration components form the basis of contemporary peatland conservation strategies.

2.3 Restoration economy and community livelihoods

Recent peatland restoration initiatives increasingly recognize that ecological recovery cannot be sustained without addressing community livelihood needs. Restoration economy refers to economic activities that support ecosystem restoration while generating social and economic benefits for local communities. Rather than viewing conservation and development as competing objectives, the restoration economy seeks to align environmental recovery with sustainable livelihoods.

In peatland landscapes, restoration-based economic activities may include paludiculture, freshwater fisheries, non-burning agriculture, ecotourism, nursery development, and sustainable forest-product utilization [14]. These activities can reduce community dependence on environmentally destructive practices such as illegal logging, peatland drainage, and land clearing through fire.

The restoration economy concept is particularly relevant in Indonesia because peatland restoration occurs within inhabited landscapes where local communities depend on natural resources for their livelihoods. Consequently, restoration success depends not only on ecological interventions but also on the availability of economically viable and socially acceptable livelihood alternatives. Integrating restoration economy into conservation programmes can therefore enhance community participation, reduce restoration conflicts, and improve long-term restoration sustainability.

2.4 Science-supported ecological monitoring and prospective molecular and biological applications

Science-supported ecological monitoring refers to the systematic use of ecological, hydrological, spatial, and biological information to assess ecosystem condition and restoration progress. In peatland contexts, currently implemented approaches commonly include species inventories, camera traps, water-table observations, remote sensing, satellite imagery, and field validation. These tools generate baseline and trend information, although their ability to demonstrate ecological recovery depends on repeated measurements and appropriate counterfactual or baseline comparisons.

For conceptual clarity, this study distinguishes three categories of science-supported approaches. First, molecular monitoring tools refer to DNA-based methods used primarily for biodiversity detection and species identification, including eDNA and DNA barcoding [15]. Second, biological restoration applications refer to biologically based interventions that may directly support ecosystem rehabilitation, including tissue-culture propagation and microbial approaches to peat-soil recovery [16]. Third, ecological and spatial monitoring tools include species inventories, camera traps, hydrological observations, remote sensing, and GIS-based analysis. The first two categories remain prospective in the Kampar Peninsula unless direct site-specific implementation is documented, whereas several ecological and spatial monitoring approaches are already represented in the available case evidence.

Bioindicator development is a bridge between ecological monitoring and biological assessment. Organisms such as Odonata, aquatic macroinvertebrates, and microbial communities may indicate habitat or water-quality conditions. Nevertheless, a species inventory is primarily a baseline record; demonstrating ecological improvement requires repeated, comparable observations showing changes through time or differences against reference conditions.

Accordingly, this study classifies camera traps, remote sensing, ecological surveys, and hydrological observations as implemented, science-supported monitoring tools. eDNA, DNA barcoding, tissue culture, and microbial restoration are discussed as prospective biotechnology applications for future testing in the Kampar Peninsula.

2.5 Policy and institutional context in Indonesia

Peatland protection in Indonesia is governed principally by Government Regulation No. 71 of 2014 on Peat Ecosystem Protection and Management, as amended by Government Regulation No. 57 of 2016 [17, 18]. These regulations establish the national basis for peat ecosystem protection, management, restoration, and control of degradation [19, 20].

Institutional implementation involves national and subnational agencies, concession holders, conservation organizations, researchers, and local communities. Ecosystem restoration concessions such as the RER initiative provide one governance arrangement for long-term protection, assessment, restoration, and management of peat-swamp forest landscapes [9].

These policy developments reflect a broader shift from protection-oriented conservation toward integrated landscape governance that combines ecological restoration, environmental-impact reduction, community participation, and climate-mitigation objectives. Such integration is increasingly important for achieving Indonesia's FOLU Net Sink 2030 target and other national sustainability commitments.

2.6 Analytical framework and research propositions

The literature reviewed above shows that peatland degradation produces interconnected environmental impacts, while restoration research often examines hydrology, biodiversity, governance, or livelihoods separately [2, 3, 7, 9]. Less attention has been given to an integrated framework that also distinguishes between intervention indicators, observed environmental conditions, expected effects, and verified ecological outcomes.

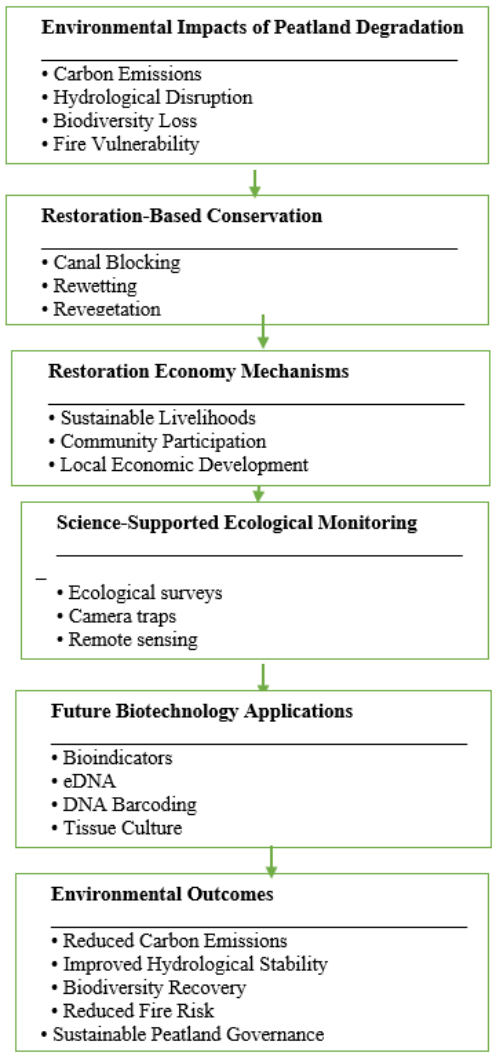

Figure 1. Analytical structure and evidence pathways for the Kampar Peninsula case synthesis

This study argues that effective peatland governance requires the integration of hydrological restoration, habitat protection, community livelihood strategies, and repeated science-supported monitoring. Canal blocking and revegetation are interventions intended to address degradation, but evidence of reduced emissions, lower fire occurrence, or biodiversity recovery requires outcome-specific measurements over time. Monitoring therefore functions not as proof of recovery by itself, but as the mechanism through which restoration claims can be tested.

For analytical purposes, the literature synthesis is organized around four interrelated domains: environmental pressures, restoration interventions, restoration-economy mechanisms, and science-supported monitoring. These domains constitute an analytical structure used to organize and interrogate the Kampar evidence rather than a validated restoration framework. Within the monitoring domain, ecological surveys, camera traps, remote sensing/GIS, and hydrological observations represent documented monitoring approaches, whereas molecular monitoring tools and other biological restoration applications are treated as prospective extensions requiring site-specific validation. Figure 1 summarizes these analytical relationships and the evidence pathway subsequently examined through the Kampar Peninsula case synthesis.

The interaction among these components is expected to support improved environmental governance, but the strength of each claimed outcome depends on the available evidence. Activity indicators describe what has been implemented; condition indicators document the state of the ecosystem; and outcome indicators are required to demonstrate changes such as water-table recovery, declining fire incidence, reduced emissions, or biodiversity trends. The framework therefore emphasizes evidence pathways rather than assuming that restoration activity automatically produces ecological recovery.

Accordingly, this study is guided by three analytical propositions:

P1. Hydrological restoration and revegetation are expected to reduce degradation pressures, but their ecological effects should be evaluated using repeated hydrological, carbon, fire, and vegetation indicators.

P2. Restoration-based economic activities may strengthen participation and reduce pressure on peatland resources when livelihood benefits and behavioral changes are sustained and documented.

P3. Science-supported monitoring improves restoration assessment by generating baseline and trend evidence, while biotechnology applications require site-specific implementation and validation before their contribution can be established.

These propositions provide the analytical basis for evaluating restoration initiatives in the Kampar Peninsula and for developing an integrated conservation framework applicable to tropical peatland landscapes.

3. METHODOLOGY

3.1 Research design

This study employed a qualitative case-study synthesis based exclusively on secondary data to examine peatland degradation, restoration interventions, livelihood programmes, and monitoring practices in the Kampar Peninsula, Riau, Indonesia. More specifically, the research used a structured literature- and document-based case analysis in which the Kampar Peninsula served as the bounded analytical case. No primary data were collected through interviews, surveys, participant observation, or direct field observation. The case was selected because the landscape has experienced substantial land-use change and has been the focus of a long-term ecosystem-restoration programme, providing a sufficiently documented setting for synthesizing ecological, socio-economic, institutional, and monitoring evidence.

The unit of analysis was the restoration-governance system of the Kampar Peninsula. Evidence was coded into four domains: environmental pressures and impacts; restoration activities; restoration-economy activities; and monitoring evidence. The analysis deliberately distinguished implementation indicators (for example, concession area or canal length), observed condition indicators (for example, species records), and verified outcome indicators (for example, measured changes in groundwater level, fire incidence, carbon flux, or population trends).

3.2 Study area

The study focuses on the Kampar Peninsula, located in Riau Province, Sumatra, Indonesia. The area is situated between the Kampar and Siak river systems and contains extensive peat swamp forests characterized by deep peat deposits, high carbon-storage potential, and significant biodiversity value.

The Kampar Peninsula has experienced substantial environmental pressures resulting from industrial timber plantations, oil palm expansion, drainage infrastructure development, logging activities, and recurrent peat fires. At the same time, the landscape has become an important restoration site under the RER initiative, making it an appropriate case for evaluating peatland restoration effectiveness and environmental-impact mitigation strategies.

3.3 Data sources

This study relies exclusively on secondary data obtained from multiple authoritative sources. The use of secondary data is appropriate because the objective of the study is to synthesize existing ecological, restoration, biodiversity, and governance evidence into an integrated conservation framework.

The review covered English- and Indonesian-language materials published from 2003 through 2025, with emphasis on studies and reports concerning the Kampar Peninsula and comparable Indonesian tropical peatlands. Searches were conducted using Scopus, Google Scholar, ScienceDirect, SpringerLink, and publisher platforms, supplemented by official Indonesian legal repositories and the publication repositories of RER and relevant restoration institutions. Search strings combined terms such as ‘Kampar Peninsula,’ ‘peatland degradation,’ ‘peat restoration,’ ‘canal blocking,’ ‘Riau Ecosystem Restoration,’ ‘biodiversity monitoring,’ ‘community livelihood,’ ‘camera trap,’ and ‘remote sensing.’

Documents were eligible when they: (1) addressed the Kampar Peninsula or provided directly relevant evidence from comparable tropical peatlands; (2) reported land-cover, hydrological, biodiversity, fire, carbon, governance, or livelihood information; (3) described a restoration or monitoring intervention; and (4) were peer-reviewed publications, official regulations, government documents, or identifiable institutional reports. Commentary without traceable evidence, duplicate records, and sources that did not permit attribution of the reported information were excluded.

Data extraction used a structured matrix recording the source, publication year, study area, evidence type, implementation period, intervention scale, indicator, reported observation, and limitation. Numerical values were retained only when a specific source could be identified. Evidence from

peer-reviewed studies was compared with institutional and policy documents; where direct outcome measurements were unavailable, the manuscript reports activities or expected effects rather than verified ecological recovery. The principal categories of secondary data, the indicators examined, and their corresponding sources are summarized in Table 1.

Table 1. Secondary data sources used in the study

Data Category	Indicator	Main Sources
Land-use change	Forest cover change, peatland conversion	Sari et al. [7]; Novarina et al. [8],
Hydrology	Canal systems, groundwater restoration	Jaenicke et al. [3]; Ritzema et al. [10]; RER Progress Report 2023 [19]
Biodiversity	Species inventories, conservation status	Pudyatmoko et al. [6]; RER Progress Report 2023 [19]; Dow et al. [21]
Carbon and peat conditions	Carbon stocks, peat depth, peat degradation	Wijaya et al. [5]; peer-reviewed peat studies
Governance and policy	BRGM, FOLU Net Sink, peat regulations	Government Regulations No. 71/2014 and No. 57/2016 [17, 18]
Restoration programmes	Canal blocking, revegetation, community programmes	Yuwati et al. [9]; RER Progress Report 2023 [19]

The collected documents provided information on historical land-cover change, peatland degradation indicators, biodiversity conditions, restoration interventions, environmental impacts, and community-based restoration programmes.

3.4 Data collection procedure

Data were analysed through qualitative thematic synthesis. First, evidence was coded deductively according to the four analytical domains and then inductively for recurring subthemes. Second, numerical and descriptive statements were checked against their source and classified as implementation, condition, or outcome evidence. Third, findings were triangulated across peer-reviewed, regulatory, and institutional sources. Finally, the integrated framework was developed from patterns that were supported across more than one evidence category, while unsupported or prospective claims were retained only as future research directions.

3.5 Data analysis

Data were analysed using qualitative thematic synthesis. Thematic synthesis was selected because it allows the integration of ecological, institutional, and socio-economic evidence originating from multiple data sources.

The analytical procedure consisted of four stages.

Stage 1: Environmental Impact Identification

Evidence related to environmental impacts of peatland degradation was identified and classified into four categories: (1) carbon emissions and carbon-stock loss; (2) hydrological degradation; (3) biodiversity loss; (4) fire vulnerability and land-use pressures.

Stage 2: Restoration Intervention Assessment

Restoration activities implemented in the Kampar Peninsula were analysed according to their primary objectives and ecological functions. Particular attention was given to hydrological restoration, revegetation programmes, biodiversity monitoring, and community-based restoration initiatives.

Stage 3: Comparative Synthesis

Evidence from different sources was compared and triangulated to identify consistent patterns regarding restoration effectiveness and environmental-impact reduction. Triangulation enhanced analytical reliability by reducing dependence on a single source of information.

Stage 4: Framework Development

To improve trustworthiness, the review used source triangulation and an explicit evidence hierarchy. Peer-reviewed empirical studies and official regulations were prioritized for causal or policy claims; institutional reports were used to document programme activities and reported observations; and prospective technologies were not presented as implemented without case-specific evidence. This procedure reduces the risk of treating programme scale as equivalent to ecological effectiveness.

A transparent audit trail was maintained through the source matrix, eligibility criteria, coding categories, and activity-condition-outcome classification. The approach remains limited by the availability and comparability of secondary data, but it allows the synthesis process and the basis for each type of claim to be followed and repeated.

3.6 Research trustworthiness

To improve analytical rigor, the study applied source triangulation by comparing findings across peer-reviewed publications, government reports, restoration programme documentation, and conservation datasets. Only information that could be verified through multiple sources was incorporated into the final analysis.

In addition, the study maintained a transparent analytical process by documenting data sources, inclusion criteria, thematic coding procedures, and framework-development stages. These measures enhance the credibility and trustworthiness of the findings.

The reviewed evidence indicates substantial historical degradation in the Kampar Peninsula, including forest-cover loss, hydrological alteration, habitat fragmentation, and increased exposure to fire and carbon loss. Historical land-cover estimates reported in the literature should be interpreted as evidence of landscape change rather than as a direct measure of the subsequent effectiveness of restoration interventions [7, 8].

4. RESULTS

4.1 Environmental impacts of peatland degradation in the Kampar Peninsula

The evidence reviewed indicates that peatland degradation in the Kampar Peninsula has had substantial environmental impacts on ecosystem integrity, carbon storage functions,

hydrological stability, and biodiversity conservation. Historical land-cover records show that peat swamp forest cover declined from approximately 97% of the landscape in 1982 to approximately 63% in 2005, representing a loss of around 260,348 ha. This decline coincided with increasing allocation of peatland areas for HTI, forest concessions (HPH), and oil palm plantations.

4.1.1 Land-use change and habitat loss

Land-use conversion represents one of the most significant drivers of environmental change in the Kampar Peninsula. Forest conversion has reduced the extent of intact peat swamp forests and increased habitat fragmentation. The ecological consequences include reduced biodiversity, altered ecosystem functions, and increased vulnerability of endangered species such as the Sumatran tiger.

The Kampar Peninsula has high carbon-storage importance, but estimates vary by spatial boundary, peat depth, and method. Drainage exposes peat to aerobic decomposition and is consistently associated with carbon loss and subsidence [3, 5]. The available case materials support the presence of carbon-emission risk; they do not provide a single longitudinal estimate of emission reduction attributable to the restoration programme.

4.1.2 Hydrological impacts

Drainage infrastructure has altered natural peatland hydrology by lowering groundwater levels and increasing peat exposure to oxidation. Previous studies indicate that drainage-induced hydrological disruption contributes to peat subsidence, increased flood vulnerability, and reduced ecosystem resilience. The degradation of hydrological functions also increases the likelihood of large-scale peat fires during dry periods.

4.1.3 Carbon-emission impacts

The Kampar Peninsula contains substantial carbon reserves, estimated at approximately 7 billion tons of carbon across peatland ecosystems. Peatland drainage accelerates organic matter decomposition, transforming peatlands from carbon sinks into net carbon sources. Consequently, land conversion and drainage contribute directly to greenhouse gas emissions and undermine climate-mitigation efforts.

4.1.4 Biodiversity impacts

The Kampar Peninsula remains one of the most important biodiversity hotspots in Sumatra. However, habitat degradation has increased risks for numerous threatened species. The area's designation as an Important Bird Area (IBA), Key Biodiversity Area (KBA), and Tiger Conservation Landscape highlights the ecological significance of conservation interventions.

Collectively, these findings indicate that peatland degradation in the Kampar Peninsula should be understood as a multidimensional environmental-impact problem involving carbon emissions, hydrological instability, biodiversity decline, and ecosystem-service loss (Table 2).

The RER initiative applies a Protect-Assess-Restore-Manage model across a large peatland landscape [19]. The available records document the scale and types of activities undertaken. Because comparable before-after outcome data are incomplete, the following assessment distinguishes implementation evidence from expected ecological effects.

4.2 Assessment of restoration-based conservation interventions

The RER initiative represents one of Indonesia's largest peatland restoration programmes. The programme applies a Protect–Assess–Restore–Manage approach that integrates hydrological restoration, revegetation, biodiversity protection, and community engagement (Table 3).

Table 2. Major environmental impacts of peatland degradation in the Kampar Peninsula

Environmental Impact	Evidence	Consequences
Forest loss	97% to 63% forest cover (1982–2005)	Documented landscape fragmentation and habitat pressure
Drainage	Canal development	Expected water-table decline and higher oxidation risk
Carbon loss	Peat oxidation	Documented emission risk; site-specific reduction not quantified
Biodiversity decline	Habitat degradation	Threatened-species exposure; population trend not established
Fire vulnerability	Drained peatlands	Elevated fire and haze vulnerability in drained peat

Table 3. Evaluation of restoration interventions

Intervention	Implementation Evidence	Documented Observation	Source and Period	Outcome Evidence Needed
Canal blocking and rewetting	Canals/structures reported under RER	Restoration infrastructure implemented	RER Progress Report 2023 [19]	Repeated groundwater, subsidence, fire, and carbon data
Revegetation	Nursery and native-species planting activities	Planting effort documented	RER Progress Report 2023 [19]	Survival, regeneration, composition, and canopy recovery
Biodiversity monitoring	Inventories, camera traps, Odonata surveys	Species presence and baseline diversity documented	Pudyatmoko et al. [6]; RER [19]; Dow et al. [20]	Standardized occupancy, abundance, or community trends
Community engagement	Patrols, training, education, livelihood support	Participation activities documented	RER Progress Report 2023 [19]	Income durability, adoption, behavior, and land-pressure change

Institutional records report canal blocking, dam construction, and rewetting activities intended to raise or stabilize water levels and limit drainage [19]. Canal length and the number of structures are implementation indicators. Direct

evidence of hydrological recovery would additionally require repeated groundwater-level measurements, peat-moisture data, subsidence rates, and fire occurrence before and after intervention.

Hydrological restoration is expected to reduce peat oxidation and fire vulnerability based on established peatland science [3, 10]. In this case study, however, these effects are treated as anticipated mechanisms unless supported by site-specific longitudinal measurements.

4.2.1 Hydrological restoration

Hydrological restoration constitutes the foundation of peatland recovery. Evidence indicates that restoration activities have included canal blocking, dam construction, and rewetting measures designed to restore groundwater levels and reduce fire vulnerability. Restoration records report closure of approximately 116 km of drainage canals and the construction of multiple canal-blocking structures.

The environmental significance of hydrological restoration lies in its capacity to reduce peat oxidation, lower carbon-emission risks, stabilize peat surfaces, and improve ecosystem resilience. Therefore, hydrological restoration directly addresses the environmental impacts identified in Section 4.1.

Revegetation activities include nursery development and planting of native peatland species. These records demonstrate implementation and restoration effort. Evidence of habitat recovery would require survival rates, vegetation structure, natural regeneration, and compositional change measured over time.

4.2.2 Revegetation and ecosystem recovery

Revegetation programmes have focused on restoring native peatland vegetation through nursery development and planting activities. Native species restoration contributes to habitat reconstruction, biodiversity protection, and ecosystem-function recovery.

Biodiversity surveys and camera-trap records document the continued presence of numerous flora and fauna species, including threatened taxa [6, 19]. These observations demonstrate conservation value and provide baseline information; they do not alone show that species populations or habitat quality have recovered.

4.2.3 Biodiversity protection

Biodiversity surveys have documented hundreds of flora and fauna species within restoration areas, including numerous threatened and protected species. The persistence of key species suggests that restoration efforts contribute positively to habitat conservation.

4.3 Restoration economy and community livelihood transformation

The reviewed sources document community engagement through farmer groups, village institutions, patrol teams, environmental education, and livelihood-support activities (Table 4) [19]. These are programme outputs and participation mechanisms. Evidence of restoration-economy effectiveness would additionally require household-income trends, adoption rates, reduced reliance on damaging land uses, and persistence of benefits after programme support.

From a restoration-economy perspective, community engagement may reduce restoration conflicts and strengthen stewardship and long-term conservation outcomes when it provides viable, sustained alternatives. However, current evidence is insufficient to quantify household-level economic impacts, attribute changes in land-use behaviour to the programmes, or assess long-term socio-economic effectiveness. These remain priorities for future evaluation and research.

Table 4. Restoration economy activities in the Kampar Peninsula

Activity	Main Actors	Ecological Purpose	Socio-Economic Contribution
Nursery development	Local communities	Revegetation support	Temporary employment
Community patrols	Villages and Non-Governmental Organizations (NGOs)	Fire prevention	Environmental stewardship
Sustainable livelihood training	RER and communities	Reduce land pressure	Income diversification
Environmental education	Local stakeholders	Awareness building	Capacity development

4.4 Science-supported ecological monitoring and prospective molecular and biological applications

The findings indicate that science-supported monitoring plays an important role in documenting ecosystem conditions and strengthening the assessment of restoration activities. To avoid conflating fundamentally different techniques, the analysis distinguishes among ecological and spatial monitoring, molecular monitoring, and biological restoration applications. Ecological and spatial monitoring includes biodiversity inventories, camera traps, hydrological observations, remote sensing, and GIS-based assessment. Molecular monitoring refers specifically to DNA-based approaches such as eDNA and DNA barcoding, whereas biological restoration applications include tissue-culture propagation and microbial approaches intended to support vegetation or peat-soil recovery.

The available Kampar evidence predominantly documents ecological and spatial monitoring activities. Molecular monitoring and biological restoration applications are therefore discussed as prospective directions rather than as established components of the RER restoration programme. This distinction is important because technological potential should not be interpreted as evidence of implementation or restoration effectiveness.

4.4.1 Bioindicator development for ecosystem assessment

One potentially valuable ecological-monitoring approach identified from the Kampar Peninsula evidence is the use of biodiversity indicators for ecosystem assessment. Restoration surveys recorded approximately 94 Odonata species (dragonflies and damselflies), including numerous species classified as Vulnerable, Near Threatened, or Endangered. Because Odonata are highly sensitive to environmental changes and water quality conditions, they provide a useful basis for developing biological indicators of peatland ecosystem health.

The development of bioindicator systems contributes to

restoration evaluation by providing measurable evidence of ecological recovery beyond conventional vegetation and land-cover assessments. Consequently, bioindicator-based monitoring can improve restoration accountability and support evidence-based environmental governance.

4.4.2 Ecological and technology-supported biodiversity monitoring

Biodiversity monitoring in the Kampar Peninsula has been strengthened through ecological surveys and camera-trap monitoring programmes. Biodiversity inventories documented more than 700 flora and fauna species, while camera traps confirmed the presence of globally threatened species such as the Sumatran tiger, sun bear, pangolin, and flat-headed cat.

These findings demonstrate the ecological significance of the restoration landscape and provide evidence that habitat protection and restoration activities contribute to biodiversity persistence. Camera traps constitute a technology-supported ecological monitoring tool that enables repeated wildlife observation and can contribute to long-term assessments of species occurrence and habitat use.

4.4.3 Remote sensing and GIS-supported restoration assessment

Remote sensing and ground-truth validation have also played important roles in monitoring peatland conditions and restoration progress. Satellite-based assessments have enabled the identification of land-cover changes, peatland conversion patterns, and degradation trends across the Kampar Peninsula. Combined with field verification, these approaches provide reliable evidence regarding restoration performance and environmental impacts.

Spatial monitoring is particularly important because peatland restoration occurs across large landscapes where direct ecological observation is often difficult. Therefore, integrating spatial monitoring with biodiversity assessment and hydrological measurements enhances restoration evaluation and supports adaptive management strategies.

4.4.4 Future opportunities for molecular monitoring and biological restoration applications

Several molecular and biological approaches may complement existing restoration monitoring and intervention in future research. Molecular monitoring tools such as eDNA may enable rapid detection of biodiversity from environmental samples, while DNA barcoding can strengthen taxonomic identification. Separately, biological restoration applications such as tissue-culture propagation may support the multiplication of selected peatland plant species, while microbial approaches may warrant investigation for their potential role in peat-soil rehabilitation.

These approaches are not documented here as established components of restoration in the Kampar Peninsula. They are identified as prospective research directions whose feasibility, ecological effectiveness, cost, scalability, and compatibility with peatland conditions require site-specific field testing. Their role in the preliminary model is therefore forward-looking and complementary to, rather than a substitute for, established ecological, hydrological, and spatial monitoring.

4.5 Evidence-informed preliminary environmental impact governance model

The case synthesis suggests that peatland restoration in the Kampar Peninsula can be interpreted as a broader environmental-impact governance process rather than solely as ecological rehabilitation. Drawing on the analytical domains introduced in Section 2.6 and the evidence synthesized in Sections 4.1–4.4, this study develops an evidence-informed preliminary conceptual model linking degradation pressures, restoration responses, livelihood mechanisms, and monitoring evidence. The model is intended as an analytical synthesis of the available evidence rather than a validated or practice-tested restoration framework.

The preliminary model builds upon, rather than replaces, established restoration approaches. BRGM's Rewetting–Revegetation–Revitalization (3R) framework provides an intervention-oriented structure linking hydrological, ecological, and socio-economic restoration, while RER's PARM model provides a landscape-management cycle for conservation and restoration. The model developed in this study adds an environmental-impact governance perspective by explicitly connecting degradation pressures to intervention pathways, restoration-economy mechanisms, monitoring systems, and the evidence required to substantiate claimed outcomes.

Its distinctive analytical feature is evidence-type differentiation. Restoration infrastructure and programme activities are treated as implementation evidence; biodiversity inventories and other measurements may document ecosystem conditions; anticipated ecological benefits are treated as expected effects when longitudinal evidence is unavailable; and claims of recovery require outcome-specific evidence such as repeated groundwater measurements, fire trends, carbon dynamics, vegetation trajectories, or standardized biodiversity indicators. This structure is intended to reduce the risk of equating the scale of restoration activity with demonstrated ecological effectiveness.

The model also distinguishes between established monitoring practices and prospective scientific extensions. Ecological surveys, camera traps, hydrological observations, remote sensing, and GIS-based approaches are represented in the available case evidence, whereas molecular monitoring tools such as eDNA and DNA barcoding and biological restoration applications such as tissue culture and microbial approaches remain prospective until tested under site-specific conditions.

Accordingly, the model should be understood as a hypothesis-generating and decision-support structure that identifies relationships and evidence requirements for future investigation. Its practical utility, transferability, and causal assumptions have not been validated through primary field research or comparative implementation across multiple peatland landscapes. Future empirical testing is therefore necessary before the model can be considered a validated framework for restoration practice.

4.6 Comparison with other peatland restoration cases

The Kampar Peninsula restoration experience shares several similarities with other peatland restoration initiatives in Southeast Asia, particularly in Indonesia and Malaysia. Across these cases, hydrological restoration has consistently emerged as the most critical intervention for reducing peat degradation and fire vulnerability.

One relevant comparison is the Ex-Mega Rice Project (EMRP) area in Central Kalimantan. Following extensive drainage and land conversion during the 1990s, the region

experienced severe peat degradation, subsidence, and recurrent fires. Similar to the Kampar Peninsula, restoration efforts have focused on canal blocking, rewetting, and revegetation. However, restoration challenges in Central Kalimantan have generally been greater because of the larger scale of degradation and more extensive hydrological alteration. The Kampar Peninsula differs in that large-scale restoration has been supported through ecosystem restoration concession mechanisms and long-term private-sector involvement under the RER programme.

A second comparison can be made with Sebangau National Park in Central Kalimantan. Both landscapes contain extensive peat swamp forests with significant biodiversity value and important populations of threatened species. Restoration strategies in Sebangau and Kampar emphasize biodiversity protection, fire prevention, and hydrological recovery. However, Kampar demonstrates a stronger integration of restoration activities with community-based livelihood programmes and ecosystem restoration concession governance arrangements.

At the regional level, the North Selangor Peat Swamp Forest in Malaysia provides another useful comparison. Similar restoration measures have included hydrological rehabilitation, biodiversity monitoring, and community engagement. Nevertheless, Malaysian restoration programmes tend to operate within a more centralized governance structure, whereas peatland restoration in Indonesia requires coordination among multiple government agencies, concession holders, Non-Governmental Organizations (NGOs), and local communities. This creates additional governance complexity but also provides opportunities for broader stakeholder participation.

These comparisons indicate that hydrological restoration, biodiversity monitoring, and community participation represent common determinants of restoration success across tropical peatland landscapes. However, the Kampar Peninsula contributes a distinctive lesson through its integration of restoration economy mechanisms, long-term concession-based restoration, and science-supported monitoring. This combination suggests potential relevance for other peatland restoration contexts in which environmental impacts, community livelihoods, and ecological recovery must be addressed simultaneously. However, such relevance should be treated as a proposition for comparative testing rather than evidence of demonstrated transferability.

4.7 Policy implications

The findings of this study generate several important policy implications for peatland governance in Indonesia and other tropical peatland regions. First, peatland restoration should be positioned as an environmental-impact mitigation strategy rather than solely as an ecological rehabilitation programme. Restoration policies should explicitly target reductions in carbon-emission risks, hydrological degradation, biodiversity loss, and fire vulnerability, thereby strengthening the contribution of peatland restoration to climate-change mitigation and environmental sustainability objectives.

Second, hydrological restoration should remain the primary priority of peatland management. The evidence from the Kampar Peninsula, as well as experiences from Central Kalimantan and Malaysia, demonstrates that successful restoration depends fundamentally on maintaining peatland water-table stability. Consequently, investments in canal blocking, groundwater monitoring, and long-term hydrological maintenance should be institutionalized within restoration programmes.

Third, restoration economy mechanisms should be integrated more systematically into peatland governance frameworks. Community participation is essential for ensuring long-term restoration sustainability because restoration outcomes remain vulnerable when local communities lack viable livelihood alternatives. Policymakers should therefore promote sustainable livelihood programmes, paludiculture, community forestry, peatland-friendly agriculture, and other restoration-based economic activities that simultaneously support environmental and socio-economic objectives.

Fourth, scientific monitoring should become a core component of restoration governance. Biodiversity inventories, ecological indicators, remote sensing, eDNA, and other monitoring tools can improve restoration accountability and facilitate evidence-based decision-making. The integration of science-based monitoring into national peatland restoration programmes would strengthen evaluation mechanisms and improve adaptive management capacity.

Finally, the evidence-informed preliminary model developed in this study offers an analytical structure for considering how restoration interventions, environmental-impact reduction, community livelihoods, and monitoring evidence may be connected. At its current stage, the model should not be interpreted as a validated practical framework. Rather, it may inform the design of future pilot applications and comparative studies through which its usefulness for policymakers, restoration practitioners, and conservation organizations can be empirically evaluated.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study examined how environmental impacts of peatland degradation in the Kampar Peninsula can be addressed through the integration of restoration-based conservation, restoration economy mechanisms, and biotechnology-supported monitoring approaches. The findings demonstrate that peatland degradation generates interconnected environmental impacts, including carbon-emission risks, hydrological disruption, biodiversity decline, and increased fire vulnerability. These impacts highlight the need to view peatland restoration as a broader environmental-governance challenge rather than merely an ecological rehabilitation activity.

The analysis shows that restoration interventions implemented through the RER programme have contributed to environmental recovery through hydrological restoration, revegetation, biodiversity protection, and community engagement. However, restoration effectiveness depends not only on ecological interventions but also on the ability to create sustainable livelihood opportunities and maintain long-term monitoring systems.

The principal contribution of this study is an evidence-informed preliminary conceptual model that connects environmental-impact pressures, restoration interventions, restoration-economy mechanisms, and science-supported monitoring while explicitly differentiating among implementation evidence, observed conditions, expected effects, and verified outcomes. Rather than replacing BRGM's 3R approach or RER's PARM model, the proposed model

complements these established approaches by adding an evidence-oriented environmental-governance layer. This distinction encourages restoration effectiveness to be assessed through outcome-specific evidence rather than inferred from programme activities alone.

The model remains preliminary. Because it was developed through secondary-data synthesis of a single restoration landscape, its causal relationships, practical utility, and transferability have not been empirically validated. Its value at this stage lies in organizing available evidence, identifying gaps between restoration activities and demonstrated outcomes, and generating propositions for future field-based and comparative testing.

The findings suggest that future peatland restoration initiatives should be evaluated not only in terms of restored area or infrastructure development, but also according to their contribution to environmental-impact reduction, biodiversity recovery, governance effectiveness, and community resilience. Consequently, the proposed framework offers a scalable approach for strengthening tropical peatland restoration and supporting broader climate-change mitigation and sustainable-development objectives.

5.2 Recommendations

Based on the findings of this study, several strategic recommendations are proposed to strengthen peatland ecosystem conservation in the Kampar Peninsula and similar tropical peatland landscapes in Indonesia. First, long-term hydrological restoration must be prioritized through continuous monitoring and maintenance of canal blocking infrastructure, dams, and rewetting systems, as hydrological stability is the most critical determinant of peatland resilience and fire prevention. Second, revegetation programs should be expanded by strengthening nursery development and scaling up the planting of peatland-native species, particularly those with high ecological and conservation value, to accelerate habitat recovery and improve biodiversity protection. Third, molecular monitoring tools and biological restoration applications should be evaluated through carefully designed pilot studies before wider integration into restoration programmes. Potential applications include eDNA and DNA barcoding for biodiversity monitoring, tissue-culture propagation for selected peatland plants, and microbial approaches for peat-soil rehabilitation. Such applications should be assessed for ecological validity, feasibility, cost-effectiveness, scalability, and compatibility with site-specific peatland conditions. Fourth, restoration economy mechanisms should be reinforced by developing sustainable livelihood programs such as paludiculture, freshwater fisheries, eco-tourism, and non-burning agriculture, ensuring that peatland conservation provides tangible socio-economic benefits to local communities and reduces pressures for illegal land conversion. Fifth, stronger governance coordination is required among BRGM, local governments, private restoration concession holders, NGOs, and community institutions to reduce institutional fragmentation and ensure integrated peatland management at the landscape level. Sixth, scientific infrastructure and research collaboration should be strengthened through long-term monitoring stations and ecological research facilities to increase evidence-based restoration planning and produce peer-reviewed scientific outputs that support national policy development. Finally, regulatory enforcement must be improved to address illegal burning, drainage practices, and land conversion, accompanied by conflict resolution mechanisms to manage competing land-use interests between conservation priorities and industrial plantation development.

5.3 Study limitations and future research

Several limitations should be acknowledged. First, this study is based exclusively on secondary evidence and does not include primary data collection through stakeholder interviews, community surveys, participant observation, or direct field observation. Consequently, the analysis cannot independently verify stakeholder experiences, implementation processes, or site-level ecological changes beyond those documented in the reviewed sources. Second, the study does not provide direct longitudinal measurement of restoration outcomes such as carbon-emission reductions, groundwater recovery rates, biodiversity population trends, or household-level socio-economic impacts. Third, the analysis focuses on a single restoration landscape, which limits the extent to which the proposed preliminary conceptual model can be generalized or transferred to peatland regions with different ecological, institutional, and socio-economic conditions.

Future research should incorporate longitudinal ecological datasets and quantitative environmental indicators to evaluate restoration effectiveness more rigorously. Studies examining carbon dynamics, hydrological recovery, biodiversity trends, and socio-economic impacts would strengthen understanding of restoration outcomes. Future investigations should also explore the practical application of biotechnology-supported conservation tools, including eDNA, DNA barcoding, microbial restoration, and tissue-culture propagation, to assess their effectiveness in tropical peatland restoration programmes.

Future research should also undertake primary field validation of the preliminary model through stakeholder interviews, community-based research, direct ecological observation, and longitudinal monitoring. Such research would allow the relationships proposed in the model to be examined from both governance and ecological perspectives and would provide a basis for refining, testing, or rejecting individual components of the model.

Comparative studies across multiple peatland landscapes in Indonesia and Southeast Asia would further enhance understanding of how restoration economy mechanisms, governance arrangements, and environmental monitoring systems influence restoration success under different institutional and ecological contexts.

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