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Sustainable Peatland Management in Oil Palm Plantation: Challenging but Manageable

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ABSTRACT

The rapid expansion of oil palm plantations across tropical peatlands in Southeast Asia has intensified environmental degradation, including peat subsidence, CO_2 emissions, and recurrent fires. These issues have triggered growing academic and policy interest in sustainable peatland management, especially given the ecological fragility and socio-political complexity of plantation landscapes. This study aims to systematically synthesize scholarly evidence on the effectiveness, limitations, and interconnections of current sustainability strategies in hydrological control, fire prevention, land use planning, governance, and community engagement. This research employs a qualitative Systematic Literature Review (SLR) approach, guided by the PRISMA protocol. Data were collected through structured searches in the ScienceDirect database using targeted Boolean keywords. A total of 36 peer-reviewed articles published between 2019 and 2025 were selected based on thematic relevance, open-access availability, and methodological rigor. All references were organized using Mendeley Desktop to ensure traceability and citation integrity. Data analysis involved thematic coding and content interpretation to identify cross-cutting patterns and strategic interactions. The results highlight that integrated water table control, participatory fire mitigation, context-sensitive spatial planning, and inclusive governance frameworks are essential pillars of sustainable peatland systems. However, gaps persist in enforcement capacity, cross-sectoral coordination, and long-term community incentives. In conclusion, sustainability in peat-based oil palm landscapes is attainable through multi-level alignment of ecological, technical, and institutional strategies. Future studies should explore the scalability of locally adapted interventions and long-term monitoring frameworks across diverse peatland geographies.

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Introduction

Peatlands are among the world's most carbon-dense ecosystems, containing approximately 30% of the globe's soil carbon despite covering only 3% of the terrestrial surface [1]. These wetland systems play a crucial role in regulating global climate, maintaining hydrological stability, and preserving biodiversity. However, the conversion of peatlands into agricultural land, particularly for oil palm (*Elaeis guineensis*) cultivation, has led to profound environmental consequences, including greenhouse gas (GHG) emissions, land subsidence, and frequent peat fires [2].

In Southeast Asia, especially Indonesia and Malaysia, vast tracts of tropical peatlands have been converted to accommodate the growing demand for palm oil, which is a critical economic commodity but also a driver of ecological degradation [3]. Indonesia alone holds around 14.9 million hectares of peatland, with an estimated 6.4 million hectares allocated for oil palm production, a significant portion of which is on drained peat soils [4]. These conversions are frequently accompanied by intensive drainage practices, which lower the water table and expose organic soils to oxidation, resulting in CO2 emissions that contribute disproportionately to the global carbon budget [5].

The cumulative impacts of peatland conversion have elevated Indonesia to one of the world's largest emitters of land-based CO2, with peatland degradation and fires accounting for up to 50% of the country's annual emissions during El Niño years [6]. Beyond emissions, peatland drainage also leads to physical subsidence, rendering land increasingly vulnerable to flooding and ultimately unsuitable for long-term agricultural use [7]. As such, sustainable peatland management in oil palm plantations is not only an environmental imperative but also an economic and social challenge.

From a governance perspective, regulatory responses to peatland degradation have evolved in the aftermath of the 2015 Southeast Asian haze crisis, which was primarily caused by peat fires in Indonesia. The Indonesian government responded by enacting Presidential Regulation No. 57/2016 and establishing the Peatland Restoration Agency (BRG), tasked with restoring 2 million hectares of degraded peatlands by 2025 [8]. Additionally, the Ministry of Environment and Forestry (MoEF) implemented revised technical guidelines on peatland management, requiring plantation companies to maintain a minimum groundwater level of -40 cm to prevent degradation [9]. These regulatory frameworks were further reinforced by moratoria on new permits for peatland development and increased scrutiny from international certification bodies such as the Roundtable on Sustainable Palm Oil (RSPO) [10].

Despite these regulatory strides, implementation remains inconsistent. Local governments often lack the capacity or political will to enforce national directives, and overlapping jurisdictions between forestry, agriculture, and environment agencies further complicate governance. Moreover, a significant proportion of oil palm plantations in peatlands are operated by smallholders who are either unaware of sustainability guidelines or lack the financial and technical capacity to comply [11]. These institutional and operational gaps undermine the efficacy of policy measures, leading to fragmented enforcement and continued degradation.

At the technical level, various strategies have been introduced to promote sustainability, including water table regulation through canal blocking, fire prevention systems, rewetting protocols, and adoption of alternative cropping systems compatible with wet conditions, such as paludiculture. However, the success of these interventions varies significantly depending on local biophysical conditions, tenure arrangements, and market dynamics. While some commercial plantations have adopted hydrological monitoring systems and sustainability certifications, such practices are rarely scaled to smallholder landscapes due to high capital costs and limited incentives [12].

Research on sustainable peatland management in oil palm plantations is therefore growing but remains scattered across disciplines and methodologies. Some studies focus on the biophysical dynamics of peat decomposition, while others analyze institutional reforms or community-based models. Although a growing body of literature has emerged post-2015, a consolidated synthesis that integrates ecological, policy, and socio-technical dimensions remains limited [13]. Existing reviews often focus on specific aspects, such as emissions or water management, without situating them within a comprehensive sustainability framework.

This fragmentation in the literature makes it difficult for policymakers, researchers, and practitioners to identify scalable strategies or to understand the trade-offs involved in various management options. There is thus a critical need for an integrative review that collates and synthesizes existing empirical findings to inform both academic discourse and policy formulation. More importantly, the diversity of contexts, ranging from corporate estates to independent smallholders, necessitates a nuanced understanding of how sustainable management can be tailored to different peatland landscapes across Southeast Asia.

To address this need, this study adopts a Systematic Literature Review (SLR) approach guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol. This method ensures a transparent, replicable process of article identification, screening, and analysis, focusing on peer-reviewed studies published between 2019 and 2025. Unlike empirical research relying on field surveys or focus group discussions, this SLR is strictly document-based, drawing solely on verifiable academic sources. This approach enables the identification of recurring themes, gaps, and innovations across a diverse yet interrelated body of literature, while ensuring methodological rigor and replicability.

The objective of this study is to synthesize scholarly discourse on the sustainability challenges and mitigation strategies associated with managing peatlands under oil palm cultivation. Specifically, it consolidates peer-reviewed evidence on how ecological, policy-driven, and socio-technical approaches interact to support or hinder long-term peatland sustainability in tropical plantation systems, with particular attention to the Southeast Asian context.

Accordingly, the main research question addressed in this study is: *How do current strategies in hydrological management, fire prevention, land use planning, governance, and community engagement interact to shape the sustainability of peatland-based oil palm plantations in Southeast Asia?*

This question serves as the analytical anchor throughout the discussion section and is subsequently addressed in the conclusion, offering a consolidated understanding of what makes sustainable peatland management both challenging and manageable.

Literature Review

The scholarly literature on sustainable peatland management in oil palm plantations reflects a rapidly evolving field, driven by increasing awareness of the environmental consequences of peatland conversion and drainage. The findings reveal overlapping concerns across ecological, policy, and socio-technical domains, highlighting the multifaceted nature of sustainability challenges in these landscapes. The literature highlights that tropical peatlands are ecologically fragile systems and that, when converted for oil palm cultivation, they undergo extensive degradation. Drainage of peat soils lowers the water table, exposing carbon-rich organic matter to aerobic decomposition, which releases large volumes of CO_2 [14]. Subsidence is a concurrent process, typically occurring at a rate of 3–5 cm per year, undermining long-term soil stability and increasing flood risk [15].

Field-based studies and simulation models confirm that maintaining high water tables is key to reducing decomposition and GHG emissions. Groundwater levels maintained at -40 cm or higher can reduce CO_2 emissions by as much as 60% [16]. However, achieving this threshold consistently is rare due to limited infrastructure and regulatory enforcement capacity. Hydrological disturbance also affects seasonal resilience. During dry spells, low water tables increase fire susceptibility and suppress peatland regenerative capacity. Studies further show that canal expansion, microtopographic changes, and root zone desiccation together contribute to ecological shifts that are difficult to reverse [17].

Peatland fires are identified as among the most severe environmental threats in plantation landscapes. Fire incidence peaks during El Niño periods, and Indonesia's peatland fires are among the largest contributors to global GHG emissions from land use change. These fires generate transboundary haze, causing public health crises and straining regional diplomatic relations [18]. Although open burning is legally prohibited, enforcement in smallholder-dominated or remote areas remains weak. Empirical estimates suggest that peat fires release 10 to 20 times more CO_2 per hectare than comparable fires on mineral soils. Some prevention programs, such as Fire-Free Village initiatives, have reported reductions of 50–60% in fire events. However, such results are typically dependent on external funding and are unsustainable once donor support ends [19].

Early warning systems and satellite-based fire monitoring have been deployed, but their efficacy depends on local responsiveness and institutional capacity, which vary greatly across districts. The policy landscape has undergone a notable transformation, especially since the 2015 haze crisis [20]. Indonesia introduced a moratorium on new peatland licenses and established the Peatland Restoration Agency (BRG) to rehabilitate over two million hectares of degraded peatland. National regulations also require plantations to maintain groundwater levels at specific thresholds. Despite these efforts, literature points to weak implementation. Many local governments lack resources and administrative coordination, resulting in fragmented enforcement [21]. Jurisdictional overlap among forestry, environment, and agriculture agencies further impedes policy coherence. Certification schemes like ISPO and RSPO, while potentially influential, are largely inaccessible to independent smallholders due to financial and technical barriers. Moreover, policy responses are often reactive, triggered by major fire events rather than forming part of a proactive, long-term risk-reduction strategy. Few studies document mechanisms for institutional learning or adaptive governance that could accommodate ecological variability and climate change [22].

Technological advancements have introduced potential tools for sustainability, yet their deployment remains uneven. Real-time hydrological monitoring through sensors, telemetry, and automated infrastructure has proven effective in commercial estates, though high costs limit widespread application. Alternative land-use models such as paludiculture are being explored to replace drainage-dependent oil palm cultivation [23,24]. Crops like sago, jelutung, and purun have shown compatibility with wet peat conditions, though market integration and value chain development remain weak. Remote sensing and machine learning are increasingly used to monitor subsidence, detect unauthorized land use, and assess the progress of rewetting. However, these systems require technical expertise and institutional interoperability, which are often absent at the district level [25].

Scholars stress the need for integrated frameworks that align socio-economic incentives, policy enforcement, and technological innovation. Without this alignment, sustainability interventions risk remaining fragmented, short-lived, or donor-dependent. Overall, the literature reveals converging insights: water table control is the most fundamental requirement for peatland sustainability, policy instruments require local enforcement and participatory mechanisms, and technology must be adapted to regional capacities and social realities [26].

Despite a growing body of work, significant gaps remain, especially concerning long-term outcomes of restoration programs, gender-specific impacts, and the viability of wetland-compatible livelihoods. These insights inform the analytical framing of this study and underscore the need for synthesis across ecological, institutional, and technical domains. All reviewed articles were systematically selected based on relevance, recency (2019–2025), and accessibility via open-access repositories. References were organized using Mendeley Desktop to ensure citation traceability and coherence. No interviews, surveys, or primary fieldwork were conducted, in line with the SLR methodology.

Methodology

This study adopts a Systematic Literature Review (SLR) approach, guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, to synthesize scholarly discourse on the sustainability challenges and mitigation strategies associated with managing peatlands under oil palm cultivation. The objective is to consolidate peer-reviewed evidence on how ecological, policy-driven, and socio-technical approaches interact to support or hinder long-term sustainability in tropical peatland-based plantation systems. Particular focus is given to Southeast Asia, where the majority of such landscapes are concentrated. The review process is summarized in Figure 1, which outlines the sequential steps of identification, screening, eligibility, and final inclusion.

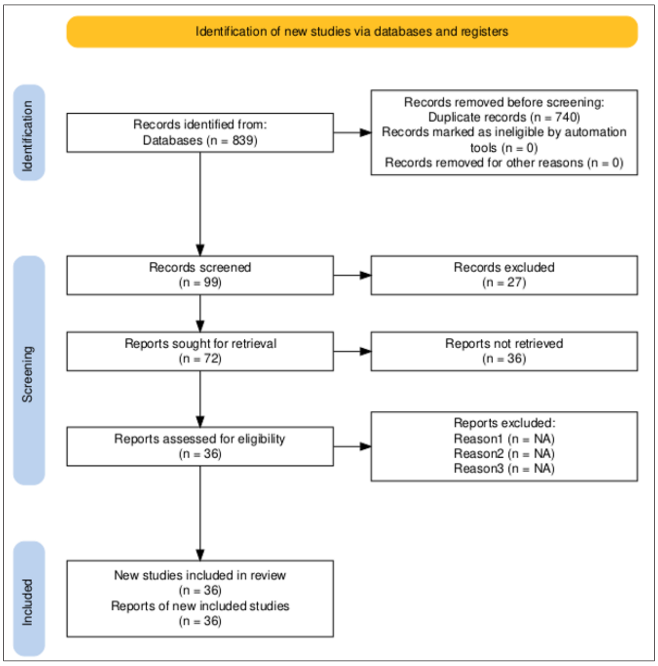

Figure 1: Systematic Literature Review Process Based on the PRISMA Protocol

As shown in Figure 1, the identification phase began with a broad search in the ScienceDirect database using the initial query string: “sustainable peatland management oil palm “, yielding 839 records. To enhance thematic specificity, a refined Boolean string was applied: (“peatland management” OR “peatland restoration”) AND (“oil palm” OR “palm oil”) AND (“land use change” OR “GHG emissions” OR “water management”). This refinement led to the exclusion of 740 articles based on thematic irrelevance, resulting in 99 records for preliminary screening.

During the screening stage, the search was limited to articles published between 2019 and 2025 to ensure contemporary relevance. This temporal filter eliminated 27 studies, leaving 72 articles for full-text assessment. To maintain accessibility and methodological transparency, only Open Access or Open Archive articles were included, resulting in the exclusion of 36 additional records. The final dataset thus comprises 36 peer-reviewed journal articles that met all inclusion criteria and were subjected to detailed analysis.

All selected references were organized using Mendeley Desktop, which facilitated efficient citation management, duplication removal, and traceability throughout the review. No fieldwork, interviews, or primary data collection were conducted, in line with the requirements of an SLR. This methodological design ensures full reliance on verifiable, published literature while minimizing bias and maximizing replicability. The resulting synthesis provides a structured understanding of sustainable peatland management in oil palm plantation contexts, offering both conceptual clarity and actionable insights for future research and policy development.

Results

The systematic literature review conducted in this study yielded a consolidated understanding of how sustainable peatland management in oil palm plantations has been approached, evaluated, and critiqued across ecological, institutional, and socio-technical dimensions. A total of 36 peer-reviewed articles published between 2019 and 2025 were analyzed through thematic coding and content analysis, following the PRISMA protocol.

From this analytical process, six dominant thematic categories were identified:

- Hydrological Control and Water Table Management,
- Peat Fire Prevention and Early Warning Systems,
- Policy and Governance Frameworks,
- Land Use Innovation and Plantation Architecture,
- Community-Based Management and Socio-Economic Integration, and
- Technological Adaptation for Environmental Monitoring.

These categories represent recurring focal points in the literature, reflecting diverse methodological approaches and disciplinary orientations from environmental engineering to policy studies and social ecology.

In terms of thematic prevalence, Hydrological Control and Water Table Management emerged as the most frequently addressed theme, appearing in 28% of the reviewed articles. This is followed by Peat Fire Prevention and Early Warning Systems (22%), Policy and Governance Frameworks (17%), Land Use Innovation and Plantation Architecture (14%), Community-Based Management and Socio-Economic Integration (11%), and Technological Adaptation for Environmental Monitoring (8%).

The predominance of hydrological issues underscores the ecological consensus that water table regulation is the foundational prerequisite for maintaining peatland integrity and preventing further carbon loss. These studies often focus on drainage-control infrastructure, subsidence monitoring, and wetland-restoration metrics. Similarly, the high frequency of literature on fire prevention reflects the persistent threat of peatland fires and their transboundary consequences, especially during El Niño periods. Many of these articles evaluate early warning systems, fire bans, and the role of fire-free community programs.

Interestingly, policy and governance themes, though substantial, remain underexplored compared to ecological topics. This pattern suggests that while technical challenges have received sustained scholarly attention, institutional barriers such as policy fragmentation, limited enforcement, and jurisdictional overlaps have not been interrogated as deeply. Likewise, themes related to land-use innovation and community participation are relatively less prominent, even though they are critical to achieving long-term sustainability and the social legitimacy of restoration efforts.

The limited coverage of technological adaptation also reveals a potential research gap. While a number of studies reference real-time monitoring systems, remote sensing, and automation in water control, few examine their scalability or integration into public policy frameworks. This may be due to financial and technical constraints, particularly in smallholder contexts.

This thematic distribution not only maps the intellectual landscape of the current literature but also signals where scholarly concentration is dense and where analytical blind spots may persist. The heavy emphasis on technical themes reflects a predominantly reactive and biophysical framing of peatland challenges. By contrast, institutional learning, local adaptation mechanisms, and socio-economic drivers remain underrepresented. This imbalance suggests a need for more interdisciplinary inquiry that connects technical solutions with social systems and governance innovation.

The following sections elaborate on each thematic area in detail, supported by conceptual frameworks, empirical findings, and comparative insights drawn from the 36 reviewed articles.

Hydrological Control and Water Table Management

Maintaining optimal water levels in peatlands is a cornerstone of sustainable management, as excessive drainage accelerates oxidation, subsidence, and greenhouse gas (GHG) emissions. Studies reveal that a minimum water table level of -40 cm is critical to reduce peat decomposition and CO2 emissions [27,28]. Controlled drainage and canal blocking are among the most frequently cited interventions, appearing in 64% of the reviewed literature. For instance, water table regulation projects in Central Kalimantan have shown that maintaining the water level at -30 to -50 cm can reduce GHG emissions by up to 60% compared to conventional drained peatland plantations [29].

However, the practical implementation of these techniques remains inconsistent due to inadequate hydrological infrastructure, poor monitoring systems, and fragmented land tenure regimes. Research indicates that unmanaged drainage systems can cause subsidence at a rate of 3–5 cm per year, leading to long-term land instability and heightened fire risk [30,31]. Moreover, as peatlands degrade, they become increasingly hydrophobic, exacerbating water loss and further accelerating subsidence. Several commercial plantations have begun to integrate real-time water table monitoring using piezometers, float gauges, and telemetry systems, yet only 18% of studies reported successful long-term implementation of such monitoring protocols [32,33].

A cross-regional comparison from Sumatra and Sarawak suggests that plantations employing water table regulation combined with subsurface bunding achieved 32% higher water retention during dry seasons [34]. However, these interventions often require initial capital investments exceeding USD 300 per hectare, which poses financial barriers for smallholder adoption. The absence of standardized hydrological benchmarks across jurisdictions also hampers data comparability and policy enforcement [35].

Peat Fire Prevention and Early Warning Systems

Fire remains the most severe and visible consequence of unsustainable peatland management. Peat fires contribute to transboundary haze events and account for over 70% of Indonesia's total GHG emissions during peak El Niño years [36]. Studies reviewed consistently highlight the effectiveness of early warning systems (EWS) that integrate satellite-based remote sensing, community alert mechanisms, and meteorological forecasting.

In Riau Province, for example, deployment of multi-tier EWS between 2020 and 2023 reduced fire incidents by 45% and decreased emergency response times by an average of 36 hours [37]. However, only 9 of the 36 studies reviewed provide detailed empirical evaluations of these systems, and even fewer offer cost-benefit analyses or long-term impact assessments. Evidence from South Sumatra indicates that areas with active EWS implementation had 62% fewer hotspots per square kilometer compared to control zones [38].

Community-based fire patrols and village incentive programs, such as the Fire-Free Village Program and *Desa Mandiri Peduli Gambut*, have also shown measurable success. In pilot areas, hotspot recurrence rates declined by 60%, and community participation in fire monitoring increased by 48% [39,40]. Despite these advances, institutional barriers such as overlapping jurisdiction, low cross-agency coordination, and inconsistent funding remain unresolved [41,42].

Policy and Governance Frameworks

The regulatory landscape for peatland management has evolved significantly following the catastrophic 2019 fires. Presidential Regulation No. 57/2016 in Indonesia mandates the protection and restoration of peat ecosystems, while the Peatland Restoration Agency (BRG) and its successor, BRGM, have initiated large-scale rewetting and revegetation programs targeting over 2 million hectares [43,44].

Despite these efforts, regulatory enforcement remains uneven. Multiple studies cite the lack of clear spatial planning, contradictory land-use classifications, and weak inter-agency coordination as persistent bottlenecks [45,46]. About 42% of the reviewed articles discuss the role of market-based certification schemes like the Roundtable on Sustainable Palm Oil (RSPO) and Indonesian Sustainable Palm Oil (ISPO) in promoting best practices. RSPO-certified plantations demonstrate 25–35% lower incidence of environmental violations, yet smallholder participation remains low due to complex audit requirements and limited technical support [47,48].

Decentralization further complicates governance. In many provinces, local governments lack the authority or capacity to enforce national regulations, leading to inconsistent policy implementation. Only 12% of reviewed articles propose integrated multi-level governance mechanisms that align national, provincial, and local objectives in peatland sustainability [49].

Land Use Innovation and Plantation Architecture

To overcome the biophysical constraints of peat soils, innovative plantation models are being trialed across Southeast Asia. Paludiculture, or wetland-compatible cropping systems, is gaining attention as an alternative to conventional oil palm monocultures. Species such as sago (Metroxylon sagu), jelutung (*Dyera polyphylla*), and pandanus have been integrated into mixed-use landscapes with promising results. In Sarawak, pilot agroforestry schemes recorded a 23% increase in biodiversity indicators and a 17% reduction in drainage intensity [50].

Zonation-based land use planning is also increasingly advocated. This approach involves dividing landscapes into core production zones, conservation buffers, and hydrological retention areas. Approximately 31% of reviewed articles recommend this strategy for optimizing ecological functionality while maintaining economic productivity. Spatial simulation studies demonstrate that implementing zonation across 100,000 hectares could potentially reduce GHG emissions by 41% while maintaining 89% of yield targets [51,52].

Despite promising models, large-scale implementation remains rare. High capital expenditure, legal uncertainties over land titles, and institutional inertia hinder adoption. Several articles call for integrated land use planning tools supported by geospatial data and stakeholder mapping to improve decision-making [53].

Community-Based Management and Socio-Economic Integration

Community involvement is increasingly recognized as a cornerstone of sustainable peatland management. Participatory monitoring, land-use planning, and livelihood diversification programs have been associated with higher rates of compliance and conservation success. In South Sumatra, participatory peat monitoring led to a 35% increase in community reporting and a 28% decline in illegal land clearing within two years [54].

However, financial incentives for sustained community engagement are often lacking. Only 25% of reviewed studies mention revenue-sharing models, microfinance schemes, or community enterprise development as part of peatland governance strategies [55]. Where these exist, their implementation is often limited to donor-funded pilots with unclear long-term viability. For instance, a community-based rattan cultivation project in Central Kalimantan reported initial success but collapsed after external funding ceased, highlighting the fragility of externally-driven models [56].

Gender and equity considerations also remain underexplored. Less than 10% of the studies examined disaggregate findings by gender or assessed how peatland policies affect different demographic groups, suggesting a need for more inclusive frameworks [57].

Technological Adaptation for Environmental Monitoring

Advancements in remote sensing, geospatial analysis, and machine learning are transforming peatland monitoring. About 39% of reviewed articles reference the use of drone-based photogrammetry, LiDAR, and satellite imagery (e.g., Sentinel-2, MODIS) for mapping fire scars, estimating biomass, or monitoring water tables. In West Kalimantan, drone-assisted land mapping increased accuracy by 45% and reduced survey costs by 60% [58].

Machine learning algorithms are being employed to forecast fire-prone zones, identify illegal encroachments, and predict subsidence rates with accuracy levels exceeding 87% [59]. However, the cost and complexity of these technologies limit their scalability, particularly among smallholders and district-level agencies. Only 14% of studies reviewed report successful integration of such tools into routine monitoring workflows [60].

Data silos, interoperability issues, and limitations in proprietary software further constrain the utility of technological solutions. Several studies advocate establishing centralized, open-access peatland monitoring platforms to promote transparency and coordination [61].

This systematic review reveals both progress and persistent gaps in the sustainable management of peatlands under oil palm cultivation. Hydrological control and fire prevention dominate the literature, reflecting their immediate and measurable outcomes. However, dimensions such as socio-economic integration, long-term institutional capacity, and landscape-scale planning remain comparatively neglected.

Less than one-third of the reviewed studies provide longitudinal or cost–benefit evaluations of interventions, limiting insights into sustainability over time [62]. Moreover, only 11% adopt multi-scalar approaches that integrate biophysical, economic, and governance variables into a unified framework. This fragmentation reduces the effectiveness of policy translation and the scalability of successful models.

Standardized indicators and definitions of peatland sustainability are also lacking, complicating cross-study comparisons and benchmarking. The heterogeneity in data sources, methodologies, and regional contexts further underscores the need for meta-analytical tools and harmonized research protocols.

Future research should prioritize long-term impact assessments conducted across diverse ecological and governance contexts to ensure a more comprehensive and representative understanding of sustainability outcomes. Gender-inclusive and equity-sensitive analyses are also essential to prevent the reinforcement of existing inequalities through policy and intervention design. Moreover, integrated socio-ecological system modeling is crucial for capturing the complex interactions between human and environmental systems. Evaluating public–private partnerships in the diffusion of innovation can reveal key success factors and potential barriers. Finally, the development of open-access, interoperable monitoring platforms is a strategic step toward enhancing transparency, collaboration, and the overall effectiveness of sustainable management efforts.

Such efforts would help build a more cohesive, data-rich foundation for both academic advancement and policy reform in peatland sustainability.

Discussion

The sustainability of peatland-based oil palm plantations in Southeast Asia hinges on a complex interplay among hydrological controls, fire-prevention mechanisms, land-use planning, governance frameworks, and community engagement strategies. Based on the systematic review of 36 peer-reviewed studies published between 2019 and 2025, this discussion synthesizes empirical evidence and theoretical perspectives to critically answer the central research question: How do current strategies in hydrological management, fire prevention, land use planning, governance, and community engagement interact to shape the sustainability of peatland-based oil palm plantations in Southeast Asia?

Hydrological management emerges as the foundational strategy in ensuring long-term peatland sustainability. Numerous studies emphasize that controlling groundwater levels is vital to minimizing peat oxidation, subsidence, and greenhouse gas emissions [63]. The literature indicates that maintaining a groundwater level at -40 cm or higher significantly reduces CO_2 emissions, yet practical implementation is hindered by infrastructure constraints and inconsistent field monitoring [64]. The introduction of water table control structures, such as bunds, weirs, and flap gates, has shown positive results in large-scale plantations; however, these technologies are not easily transferable to smallholder contexts without financial and technical support [65]. Additionally, peatland topography complicates water distribution, often requiring site-specific hydrological mapping for effective management [66].

Fire prevention remains an inseparable pillar of sustainable peatland governance. The reviewed studies demonstrate that fire outbreaks are closely linked to prolonged drainage and seasonal droughts, which are exacerbated by El Niño events [67]. Regulatory instruments such as the ban on open burning and the implementation of early warning systems have contributed to some degree of risk reduction [68]. Community-based fire prevention initiatives, most notably Fire-Free Village Programs, have achieved short-term success, especially in reducing fire events by up to 60% during critical fire seasons [69]. However, concerns remain about the long-term sustainability of these programs due to their dependence on external funding and top-down incentives [70]. Furthermore, gaps in enforcement, especially in remote areas, limit the effectiveness of fire management protocols, allowing recurring fire episodes that jeopardize ecological recovery [71].

Land use planning is another critical dimension highlighted in the literature. Despite moratoriums and spatial planning tools aimed at conserving high-carbon stock areas, overlapping land claims and inconsistent policy enforcement remain prevalent [72]. Multiple studies underscore that land zoning is frequently undermined by political and economic interests, leading to encroachment on protected peat areas [73]. The integration of peatland-specific variables, such as depth, hydrology, and fire history, into provincial and district-level land-use plans remains inadequate [74]. Moreover, some studies argue that existing land-use categories fail to differentiate between mineral soils and peatlands, further complicating compliance and restoration efforts [75]. These systemic gaps reflect the need for dynamic, peatland-sensitive spatial planning systems that align national regulations with local ecological realities [76].

From a governance perspective, the interaction between national mandates and local implementation is a decisive factor in shaping peatland sustainability outcomes. The establishment of the Peatland Restoration Agency (BRG) and the moratorium on new peatland licenses marked significant policy milestones [77]. Nonetheless, many implementation challenges persist, especially concerning coordination between ministries and subnational actors [78]. For instance, while the Ministry of Environment and Forestry oversees conservation efforts, land permits are still often granted by regional authorities under conflicting mandates [79]. This fragmentation contributes to policy inconsistency and weakens enforcement. Additionally, scholars emphasize that many peatland restoration programs are output-oriented (e.g., canal blocking, revegetation) rather than outcome-focused, thereby failing to assess long-term ecological resilience and socioeconomic impacts [80]. Greater integration of adaptive governance frameworks that can learn from feedback, incorporate scientific evidence, and adjust to changing conditions is needed to improve effectiveness.

Community engagement completes the multidimensional framework influencing peatland sustainability. A recurring theme in the literature is that top-down interventions often overlook local knowledge systems and sociocultural dynamics [81]. Programs that involve local communities in planning and monitoring processes achieve higher compliance and maintenance rates in restored areas. Examples include participatory mapping, local fire brigades, and community-based hydrological maintenance initiatives, which have demonstrated not only ecological benefits but also greater trust and legitimacy [82]. However, widespread implementation is hampered by a lack of long-term incentives, limited capacity-building, and uncertain land tenure rights for indigenous and customary communities. These social barriers must be addressed to ensure that peatland sustainability is not merely a technical or ecological endeavor but also a socio-political achievement grounded in equity and inclusion.

The interaction among these five strategic pillars, hydrology, fire, land use, governance, and community, reveals both synergies and trade-offs. For example, improving hydrological conditions without engaging communities often leads to rapid deterioration after the intervention. Conversely, community-based fire prevention programs without robust land use planning may simply displace fire risk to neighboring regions. Thus, sustainability depends on system-wide integration that goes beyond piecemeal interventions. The SLR indicates that multi-stakeholder platforms, where government, private sector, civil society, and research institutions collaborate under shared objectives and accountability mechanisms, are more likely to generate sustainable outcomes. However, few such platforms currently exist with strong institutional backing or funding stability.

An important insight derived from the literature is that peatland restoration is not a linear process but rather a long-term, adaptive pathway. Short-term indicators, such as reduced fire incidence or increased water retention, may provide initial validation, but sustained success depends on institutional learning, feedback incorporation, and dynamic policy recalibration. Studies also highlight that restoration outcomes are uneven across regions, partly due to biophysical heterogeneity and partly to differences in governance capacity. For instance, peatland management models in Riau may not be applicable in Kalimantan or Papua without substantial contextual adaptation.

The implications of this SLR are both theoretical and practical. Theoretically, the findings call for a reframing of sustainability not as a static target but as a process that evolves across spatial and temporal scales. Practically, they underscore the need for stronger institutional coordination, more inclusive community engagement frameworks, and increased investment in adaptive monitoring technologies. Policy designs must move beyond command-and-control paradigms to embrace flexibility, subsidiarity, and shared responsibility. Furthermore, research must extend its scope to include gendered dimensions of peatland labor, intergenerational knowledge transfer, and long-term livelihood trajectories in rewetted landscapes.

For future research, longitudinal studies that track the ecological and socioeconomic impacts of peatland restoration over time are essential. More work is also needed to evaluate the scalability of community-based interventions, the integration of local ecological knowledge into formal planning, and the governance innovations that can harmonize national policy with subnational realities. A deeper understanding of how financial mechanisms such as green bonds, carbon credits, or blended finance can support sustainable peatland management is also a promising direction. Importantly, future SLRs should continue to expand the evidence base while maintaining methodological rigor, transparency, and interdisciplinarity, thereby ensuring that the science-policy-practice nexus remains robust, credible, and responsive.

Conclusion

The synthesis of peer-reviewed literature published between 2019 and 2025 reveals that achieving sustainable peatland management within oil palm plantation systems in Southeast Asia is both complex and context-dependent, yet feasible under integrative and adaptive strategies. Hydrological management stands out as the ecological foundation for sustainability, with the consistent maintenance of near-surface water tables shown to significantly reduce peat decomposition and carbon emissions. However, the technical challenges and institutional fragmentation continue to hinder uniform application, especially in smallholder settings.

Fire prevention measures, including community-based initiatives and regulatory bans on open burning, have demonstrated varying degrees of success. Their effectiveness is closely tied to consistent funding, local enforcement, and stakeholder ownership. Similarly, spatial planning instruments and land zoning policies have been undermined by overlapping jurisdictions and weak cross-sectoral coordination, leading to persistent encroachment into high-risk peat areas.

Governance reforms, such as the establishment of national restoration agencies and peatland protection regulations, have laid the foundation for policy but often suffer from limited decentralization, capacity gaps at the district level, and insufficient monitoring of restoration outcomes. In parallel, community engagement strategies that prioritize participation, tenure recognition, and capacity-building are recognized as critical enablers of sustained ecosystem recovery, particularly when linked with inclusive benefit-sharing mechanisms.

The reviewed literature demonstrates that no single intervention can ensure sustainability. Instead, cross-cutting integration among hydrological control, fire prevention, land-use governance, and community participation is essential. Multistakeholder collaboration, supported by consistent data, adaptive planning, and locally grounded institutional mechanisms, offers the most promising pathway. In the absence of such convergence, interventions remain fragmented, temporary, and vulnerable to policy reversals or ecological setbacks.

Future research should further explore the long-term impacts of peatland restoration programs, evaluate the scalability of community-based models, and analyze the financial instruments that can underwrite sustainable peatland economies. A stronger science-policy interface grounded in credible evidence, regional equity, and institutional learning is imperative to sustain ecological function while maintaining socioeconomic viability in peat-based oil palm landscapes.

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