



Peat Fires in Indonesia: A Socio-Ecological Synthesis Based on a Literature Review of Management Approaches

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Abstract

Peatlands play a critical role in supporting Indonesia's net-zero emissions target due to their carbon storage and provide nature-based solutions. However, drainage, logging, and land-use change have degraded many peatlands in Indonesia, rendering them highly vulnerable to fire. Despite efforts to mitigate fires, fire incidents in peatlands remain a recurring challenge. This study examines peatland fire management in Indonesia using review of recent scientific literature. 10 peer-reviewed published between 2020 and 2025 were analyzed to identify common strategies, actors involved, and socio-ecological dynamics underlying fire management. Findings suggest that the most effective interventions combine technical solutions such as rewetting through canal blocking, revegetation, and weather modification technologies with meaningful community participation and multi-stakeholder collaboration. These strategies are more sustainable when supported by adaptive governance models that considers land tenure, cultural practices, and institutional capacities. The study also identified gaps in long-term impact assessments and limited integration of ecological, social, and economic factors in most existing interventions. By bringing in the ecological and social dimensions, this review offers a more integrated understanding of peatland fire management. This study contributes to informs policy directions toward sustainable fire governance based on efforts to mitigate peatland fires in Indonesia.

Keywords: mitigation, peatland fire, social-ecological approaches, systematic literature review

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Introduction

Indonesia has committed to achieving net-zero emissions (NZE) by 2060, as outlined in the Long-Term Strategy for Low Carbon and Climate Resilience 2050 submitted to the UNFCCC in 2021. Within this framework, the forest and other land use (FOLU) sector plays a key role by offsetting emissions from other sectors. Emissions from the FOLU sector are largely driven by forest and land fires, including the burning and decomposition of biomass residues (Eickemeier et al., 2019). Consequently, peatland fire mitigation has become a priority policy in the FOLU Net Sink 2030 agenda. As one of the world's largest carbon stores, peatlands are considered a vital nature-based solution to the climate crisis (Saarikoski et al., 2019; Mishra et al., 2021; Novita et al., 2022).

Peatlands are water-saturated ecosystems (Andriess, 1988), but drainage and land conversion reduce their moisture content and increase fire risk (Sinclair et al., 2020). Fires release harmful pollutants, including CO₂, CH₄, and N₂O (Couwenberg et al., 2010; Kumar et al., 2020), with carbon being the dominant compound due to its high presence in plant biomass (Hao et al., 1990). These fires accelerate atmospheric carbon release and are influenced by

both natural conditions and human activities such as land clearing and burning (Syaufina, 2008; Purnomo et al., 2019; Saharjo & Novita, 2022). In fact, over half of Indonesia's peatlands are degraded due to anthropogenic pressures like deforestation, plantation expansion, and repeated fires (Koh et al., 2011; Torrent et al., 2016). When dry, peat is highly flammable, leading to vegetation loss, soil degradation, and severe air pollution with widespread impacts on health, the economy, and the environment (Brown et al., 2015; Dini et al., 2022).

Indonesia's extensive peatlands are vulnerable to fires due to drainage for agriculture, especially for oil palm plantations (Thoha et al., 2014; Kiely et al., 2019; Nurhayati et al., 2021). In 2015, fires burned 2.6 million ha and released 1.74 Gt CO₂-eq (Saharjo & Novita, 2022). The resulting haze disrupted transportation, education, and industry in Sumatra (Koplitz et al., 2016). Central Kalimantan, in particular, experiences frequent peat fires, with large burn areas observed during El Niño years like 2006, 2015, and 2019 (Field et al., 2016; Schmidt et al., 2024). Fires often reoccur in the same locations, indicating a pattern of repeated burning exacerbated by dry seasons and land conversion (Arndt et al., 2013; S. E. Page & Hooijer, 2016; Uda et al., 2017). The

severity and frequency of tropical peatland fires have become a global concern, calling for urgent and strategic mitigation efforts (Harrison et al., 2009; Carmenta et al., 2017). Identifying fire sources and estimating burned areas are essential for effective management (Liu et al., 2014; Cattau et al., 2016). Community-based programs such as fire care groups are part of ongoing mitigation efforts (Sunanto, 2008). However, interventions in peatland fire mitigation involve complex and often non-linear interactions between ecological, social, and institutional factors (Wunder et al., 2018).

Given this complexity, a systematic understanding of current research is needed to inform more integrated and effective strategies. This study conducts a systematic literature review (SLR) of scientific publications on peatland fire management in Indonesia. It aims to analyze prevailing management approaches, stakeholder roles, policy frameworks, and technical interventions. The findings are expected to inform more targeted, evidence-based mitigation strategies, particularly for addressing recurring peat fires.

Dynamics of peatland degradation and fires in Indonesia

Peatlands are wet ecosystems formed from the accumulation of organic material from dead vegetation that has decomposed over a long period, resulting in low specific gravity (Andriessse, 1988; Saarikoski et al., 2019). Indonesia has approximately 14.93 million ha of peatlands, distributed across Sumatra (6.43 million ha), Kalimantan (4.78 million ha), Papua (3.69 million ha), and Sulawesi (23,844 ha), making it the country with the largest tropical peatland area in the world (Osaki & Tsuji, 2016). Peatlands play a crucial role in the global climate system due to their large carbon storage capacity and their function as habitats for various species (Harrison et al., 2020; Law et al., 2020). Ecosystem services from peatlands include providing clean water, supporting agriculture, improving soil fertility, sequestering carbon, and preventing fires (Yunus et al., 2024). However, more than half of Indonesia's peatlands have been degraded due to human activities such as drainage and deforestation, making them highly vulnerable to fires and contributing significantly to greenhouse gas emissions (Koh et al., 2011; Torrent et al., 2016; Kiely et al., 2019).

In 2015, about 623,304 ha of peatlands burned in Indonesia, with major impacts in Sumatra, Kalimantan, and Papua (Setyawati & Suwarsono, 2018). These fires released an estimated 1.62 million tons of CO₂, 320,000 tons of CO, and 46,000 tons of CH₄ into the atmosphere. Fires in Indonesian peatlands often recur, particularly during dry seasons (Dommain et al., 2014; Taufik et al., 2017). Studies indicate that emissions tend to decline with each repeated fire, from 206 tons of CO₂-eq ha⁻¹ in the first fire to 23 tons by the fourth fire (Konecny et al., 2016). Post-fire vegetation recovery can be improved by using spatial tools to detect burned area distribution (Liu et al., 2014). However, the success of recovery depends on various factors such as climate, soil conditions, social dynamics, and the extent of damage from initial fires. The 2015 fires were estimated to cause USD16.1 billion in economic losses, while the 2019 fires caused losses of USD5.2 billion, affecting multiple sectors including agriculture, trade, transportation, environment, public health, and education (Kiely et al.,

2019).

Recurrent fires are commonly observed during El Niño years, which contribute to the ongoing loss of carbon stocks in peatlands (Gaveau et al., 2014; Field et al., 2016). Large-scale fires in Indonesia have been linked to strong El Niño events and positive Indian Ocean Dipole (IOD) phases, which reduce rainfall and prolong dry seasons (Edwards et al., 2020; Purnomo et al., 2021; Nurdiati et al., 2022). Climate anomalies, when combined with human activities, increase fire risk significantly. Land clearing by burning remains a widely used method in agriculture due to its low cost and ability to increase soil nutrients in the short term (Ketterings et al., 1999; Bowen et al., 2001). However, this practice is unsustainable and continues to drive peatland degradation as population pressures increase the demand for agricultural land (Murdiyarsa et al., 2019).

Mitigation efforts and challenges of peatland restoration

The Indonesian government has shown its commitment to integrating climate change adaptation and sustainable development into national planning frameworks (Kementerian Lingkungan Hidup dan Kehutanan, 2021). The 2025–2045 National Long-Term Development Plan targets an emissions reduction of up to 93.5% (Republik Indonesia, 2024). One concrete step is the preparation of the Peat Ecosystem Protection and Management Plan at the regional level (Badan Perencanaan Pembangunan dan Penelitian Pengembangan Kabupaten Kubu Raya, 2021). The trend of declining emissions has begun to emerge, following the implementation of regulatory-based mitigation policies. However, budget allocations for peat restoration remain lower than those for sectors such as transportation and energy (Kementerian Lingkungan Hidup dan Kehutanan, 2019), despite the potential to reduce emissions by up to 269 Mt CO₂ year⁻¹ (Novita et al., 2022). Restoration costs are estimated at USD1.7 to 7 billion, with an average of around USD1,866 ha⁻¹ (Hansson & Dargusch, 2017; Kiely et al., 2020). Although several policies have been issued to support restoration, many are not fully aligned with field realities, and no national-scale mapping of priority restoration areas has yet been conducted (Uda et al., 2020). This underlines the need for more responsive policies, better resource allocation, and stronger multi-stakeholder involvement.

Effective peatland restoration requires an understanding of both social and biophysical dimensions (Grover et al., 2024). Mitigation strategies must be grounded in practice and generate measurable feedback (Kanngieser & Todd, 2021). Examples of practice-based approaches include the moratorium on new oil palm permits on peatlands, weather modification, early warning systems, land management incentives, and community education (Tacconi, 2016). The success of such efforts depends on the collaboration of diverse actors with complementary roles and capacities. At the local level, *Masyarakat Peduli Api* (MPA) plays a key role in preventing fires, especially those driven by anthropogenic causes. However, their effectiveness is often hampered by inadequate funding, institutional support, and firefighting infrastructure (Nurhidayah et al., 2023). Challenges include limited access to technical equipment such as portable pumps, tents, and hoses. As a volunteer-based group, MPA involvement must also consider local

social contexts and communication dynamics (Iqbal, 2007).

Peat fire management in Indonesia still faces challenges at both grassroots and policy levels. At the community level, MPAs lack sufficient resources, while at the governance level, problems such as data uncertainty, fragmented coordination, and misalignment between plans and execution persist (Budiman et al., 2021; Nurhidayah et al., 2023). Strengthening collaborative governance, such as building on stakeholder perceptions and transparent dialogue, is seen as key to ensuring the long-term sustainability of peatland restoration (Reed et al., 2016; Sukwika et al., 2022).

Socio-ecological approach in peat fire management The social-ecological system (SES) approach is a conceptual framework that explains the interconnectedness between social systems and ecosystems. Ecological systems are strongly influenced by one or more social systems (Andriess, 1988), making this framework relevant for understanding society's role in ecological conservation efforts (Cash et al., 2006). It emphasizes that interactions between subsystems affect overall system dynamics and is especially useful in analyzing complex environmental issues, including peatland fire management. Developed to balance the analysis of social and ecological dynamics, the SES framework consists of four key subsystems: resource systems, resource units, governance systems, and actors (Ostrom, 2009). The interactions among these subsystems produce action situations, which are specific outcomes that emerge from reciprocal relationships within the system.

In the context of peatland fires, SES offers a structured lens to evaluate how policies, community behaviors, and ecosystem conditions contribute to sustainability. It recognizes that social and ecological aspects are equally important, positioning them as interconnected and co-evolving (McGinnis & Ostrom, 2014; Cole et al., 2019). This perspective views humans and ecological processes as inseparable components of a shared system. This study applies the SES framework by analyzing the four subsystems based on peat ecosystem characteristics and local fire management practices. The resource system refers to the condition of the peat ecosystem, while resource units include spatial distribution and ecosystem services. On the social side, the governance system captures policies and decision-makers in fire control, and actors represent local stakeholders such as communities, institutions, and groups like MPA. Interactions among these elements generate social and ecological outcomes that provide feedback for improving peatland management (Birgé et al., 2016).

In practice, ecosystem control over peat fires is declining, indicating weaknesses in current management (Griscom et al., 2017). Strengthening an approach that integrates both social and ecological perspectives is therefore time-sensitive. These two dimensions cannot be separated, as they shape the system's behavior through continuous interaction. Humans as social beings coexist with peatlands as ecological systems, forming what are referred to as socio-ecological restoration interactions (Budiharta et al., 2016). Future restoration should ideally adopt this framework, emphasizing inclusive participation and collaboration (Fischer et al., 2021). SES also supports more open dialogue among actors, enabling a

safe space to exchange views and adapt ideas to local contexts (Toumbourou et al., 2024).

Methods

Research questions In formulating the research questions for this systematic review, an exploratory approach was applied based on the focus of the study. This study aims to identify and review strategies, practices, and challenges in peatland fire management in Indonesia that are available in scientific literature and meet the inclusion criteria. The central question of this study is: How have forest and peatland fires in Indonesia have been managed and what approaches have been applied to reduce their impact. This review also seeks to examine how various actors have contributed to fire mitigation through both direct interventions and indirect approaches.

To deepen the analysis, this study adopts a socio-ecological perspective. It considers ecological aspects, such as the occurrence of fires and the condition of the peatland ecosystem, alongside social dimensions, which include governance mechanisms and the roles of different actors involved. By applying this scope, the study explores how interactions between social systems and ecological conditions shape the effectiveness and sustainability of peatland fire management efforts.

Search strategy In conducting a systematic review, the articles considered were articles published in international scientific journals from 2020 to 2025 and focused on the application of fires in peatlands. This objective considers the relevance to the field of environmental management based on the existing database in SCOPUS. Articles were searched using the keywords: "peat", "fire", "management", "governance", "local", and "actor". Exploration was continued with a search for derivative keywords, such as "governance", "local", "knowledge", and "actor". Keywords were also combined to refine the search. Publications containing search criteria in the title, keywords, and/or abstract. To ensure the replication of studies, this study presents the searches and terms used in the database in Table 1.

Inclusion and exclusion criteria This study is a systematic review compiled based on the guidelines of Gough, Oliver, and Thomas (Gough et al., 2017) and uses an approach developed by the EPPI Centre. In addition, the review process also followed the checklist from the Joanna Briggs Institute (JBI) to see the transparency and validity of the literature studies used (Lockwood et al., 2015). This study adopts a qualitative approach, aligning with the method used in the literature reviewed. The focus of this study approach is

Table 1 Search terms

Search terms	Scopus
Peat AND Fire AND Management	
Actor	Title
Governance	ABS
Local AND Knowledge Mitigation	Key

to understand the various concepts and their characteristics. By using the inductive method, the analysis process is carried out in stages in the literature to see the knowledge and meaning contained, with the aim of developing a new understanding or theory.

The inclusion and exclusion criteria were established to maintain relevance, clarity, and manageability in the dataset. The inclusion criteria are as follows: 1) articles published between 2020 and 2025 to ensure the use of recent and contextually relevant studies; 2) studies published in peer-reviewed journals indexed in Scopus; 3) articles that discuss strategies, actors, governance, or ecological aspects related to forest and peatland fire management in Indonesia based on the keyword in the search within Scopus. The exclusion criteria include 1) articles published before 2020; 2) non-article documents such as conference proceedings, book chapters, editorials, or grey literature; and 3) studies not specifically related to the Indonesian context or not focused on the socio-ecological dimensions of fire management. These boundaries help to ensure that the review remains focused and methodological while capturing the most relevant insights from the recent literature.

Preliminary overview and study site distribution A total of 209 articles were successfully identified in the initial stage of this study, reflecting the great scientific attention to the issue of peatland fire management globally. Each article lists the location of the study, which is then mapped spatially to see its geographical distribution. The visualization results are presented in the form of a choropleth map in Figure 1. Choropleth map is a type of map that uses different shades or colors to represent the concentration or frequency of data in specific areas. In this study, the choropleth map illustrates the number of studies on peatland fire management that have been conducted in each country. The map results show that Indonesia is the center of research locations in the field of peat fire management, with a much higher number of studies than other countries. The dark green color on the map shows

that 106 articles from the total collected have study locations in Indonesia. A number of other countries, such as Australia, Russia, and Canada, also show relatively high research intensity related to the issue of peatland fires, as reflected in the maps of their regions. These four countries do have characteristics of extensive peat ecosystems that are prone to burning, so they are also the focus of international research. This finding confirms that peatland fires are a global environmental problem.

Trial flow/selection process The initial search process obtained 209 articles and then 4 filters were carried out from the database used. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) is a standardized tool used to improve the clarity and transparency of systematic review reporting (Page et al., 2021). It helps illustrate how many articles were identified, screened, excluded, and finally included. Figure 2 presents a PRISMA flowchart of the article selection process.

In the first stage, titles and keywords were reviewed to assess relevance to the topic of forest fires in the context of their management. The coverage of peatland fire issues, especially at the intersection of social and ecological aspects, and the initial collection of 209 articles need further screening to further elaborate on the socio-ecological context of this study. Many publications may discuss forest or peat fires from a technical perspective only or only from a social perspective without investigating the mixed mechanisms of both in socio-ecological-based fire management in Indonesia. Thus, a strict selection is needed to identify studies that integrate socio-ecological-based management perspectives conducted in Indonesia.

Based on the initial selection criteria, the number of articles remaining was 99. Next, a second stage of screening was carried out through abstract review, which narrowed the number of articles to 29. In the final stage, after a full reading of the contents of the documents, only 10 articles were found to be in accordance with the research focus. This selection

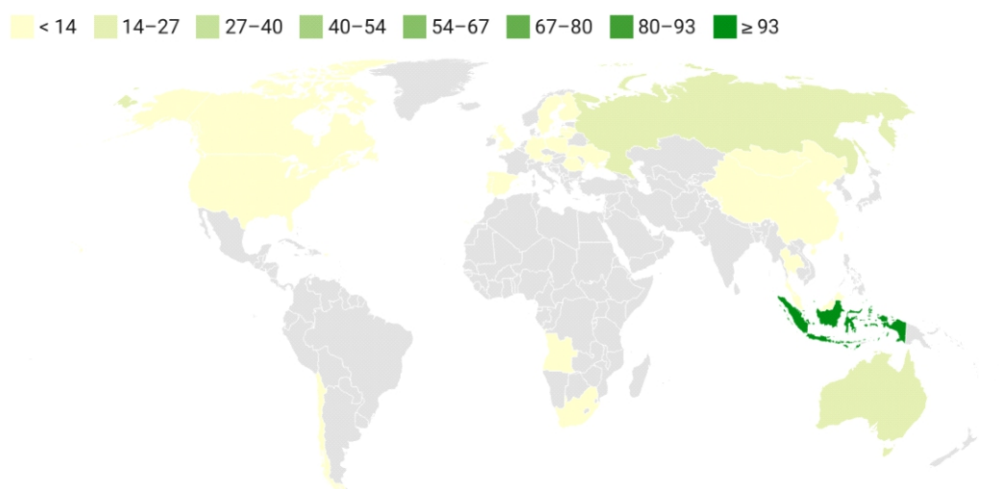


Figure 1 Choropleth map of study site distribution.

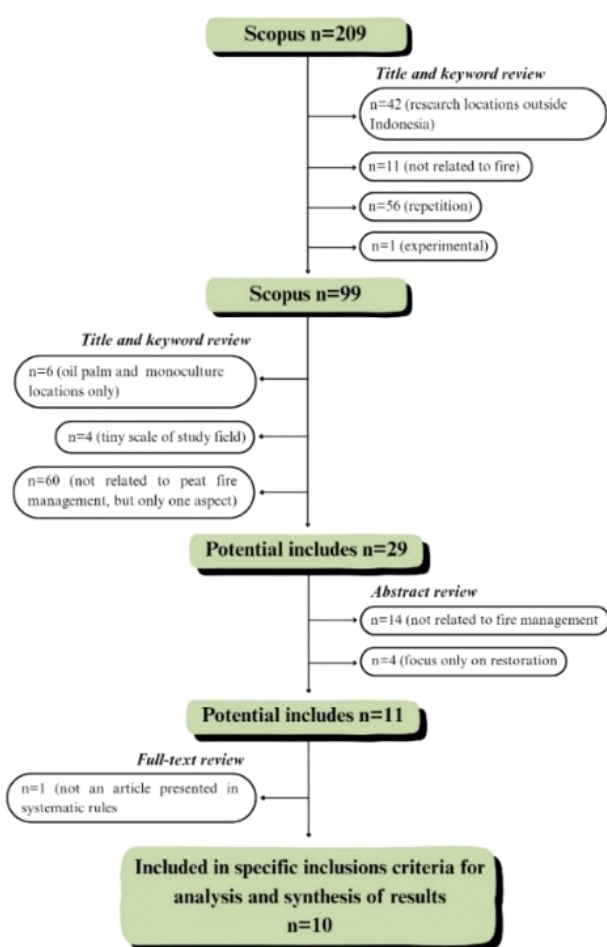


Figure 2 PRISMA flowchart for article selection process.

process was carried out by the researchers. This was possible because they used specific and tiered selection criteria. This also provided room for iterative adjustments and clarifications.

Quality assessment The quality of the reviewed articles will be assessed based on 10 control questions published by the Joanna Briggs Institute (JBI) for systematic reviews (Lockwood et al., 2015). The evaluation results of the studies obtained are presented in Table 2.

Results

This study develops several aspects of the literature analytically to systematize relevant information from the articles considered, such as study trends in year and origin of publication; methodology, such as main focus, specific focus, study approach, document type, and methodology; content studies consisting of elaboration results with a socio-ecological scope; and content studies related to action, mitigation, and conclusions of each study. This study analyzes the selected articles independently and logically with the aim of identifying the socio-ecological aspects possessed by each article. After this process, we will compare the main findings derived from the analysis of each article.

Trend in peat fire management research The scientific publication trends analyzed in this study come from the results of a strict selection based on the PRISMA method. Of the total 209 articles found through the initial search, only 10 articles were selected for further analysis. These articles have gone through the process of abstract screening, duplication removal, and full-text reading to ensure their suitability with the focus of this research study.

Based on the 10 articles that passed the full-text selection, the publication trend showed fluctuations over the past six

Table 2 Article quality control

Article	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Puspitaloka et al. (2021)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wulandari et al. (2025)	Yes	Yes	Yes	Yes	Yes	-	No	Yes	-	Yes
Imron et al. (2022)	No	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes
Usup et al. (2021)	Yes	Yes	Yes	Yes	Yes	-	No	Yes	-	Yes
Yasir et al. (2023)	Yes	Yes	Yes	Yes	Yes	-	-	-	-	Yes
Carmenta et al. (2021)	-	Yes	Yes	Yes	Yes	-	-	Yes	Yes	Yes
Robins et al. (2022)	-	Yes	Yes	-	-	-	-	Yes	-	Yes
Tan et al. (2022)	-	Yes	Yes	Yes	Yes	-	-	Yes	Yes	Yes
Sandhyavitri et al. (2023 a)	Yes	Yes	Yes	Yes	Yes	No	No	-	-	Yes
Sandhyavitri et al. (2023 b)	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes

Q1: Is there alignment between the stated philosophical perspective and the chosen research methodology?; Q2: Does the research methodology align with the research questions or objectives?; Q3: Is the chosen methodology appropriate for the data collection methods used?; Q4: Is there consistency between the methodology and how the data is presented and analysed?; Q5: Does the interpretation of the findings align with the overall research methodology?; Q6: Does the researcher identify their cultural or theoretical position within the study?; Q7: Is the potential influence of the researcher on the research—or vice versa—acknowledged?; Q8: Are participants and their perspectives clearly and adequately represented?; Q9: Was the research conducted ethically, and is there evidence of ethical approval from a relevant authority?; Q10: Do the conclusions logically follow from the data analysis and interpretation?

years (2020–2025). No articles were found that were quite relevant in 2020, but there was an increase in 2021 and a peak in 2022. After that, the trend decreased to 2 articles in 2023, and zero in 2024. 2025 showed a slight increase with 1 article that fell into the high relevance criteria.

It should be noted that Figure 3 does not reflect the total number of global publications on peatland fires but rather the number of articles that are specifically relevant and meet strict criteria based on a systematic approach and full-text reading. Thus, this trend reflects more the dynamics of research focus on socio-ecological-based topics in the selected literature than just the general volume of publications.

Social and ecological components in peat fire management research

From the late 1990s to the early 2010s, studies on peatland fire management in Indonesia have focused largely on fire prevention strategies, fire extinguishing techniques, and environmental risks due to peatland degradation (Page et al., 2009). However, since 2015, the direction of research has shifted to a broader scope, covering aspects of governance, ecosystem restoration, and the role of communities in prevention and restoration efforts (Miettinen et al., 2012; Tacconi, 2016).

Since 2020, much has been discussed about the development of prevention and restoration efforts for peatlands. The distribution of research in this study is based on four main categories, namely wildfire, ecosystem, governance, and user, and shows varying but interrelated representation. The wildfire aspect is the most dominant, with all studies reflecting ongoing concerns about the peat fires and the impacts of socio-ecological systems. Ecosystem and governance each appeared in 8 studies, focusing on the effects of fires on peat hydrology, biodiversity, policy effectiveness, law enforcement, and institutional fragmentation. Meanwhile, the user category, which includes discussions related to the role of local communities, land use dynamics, and socio-economic responses, appeared in 7 studies.

The research that has been conducted generally assesses the effectiveness of various aspects to support fire control policies on peatlands. The approach used is also carried out

more comprehensively by including 3–4 aspects in a research issue. Meanwhile, the focus of the research is considered balanced between social and ecological aspects. This indicates that both are equally important for efforts to control fires on peatlands and the sustainability of peat ecosystems.

Content study: Methodology The ten articles selected based on the research content and aligned with the objectives of this study divide peatland fire management into two main focuses: ecological and social. Six articles raise themes related to ecological aspects, such as ecosystem conditions and the dynamics of the fire itself. Meanwhile, four other articles highlight social aspects, especially in terms of institutional governance and community involvement and other stakeholders at the local level. This indicates that the study of peatland fires is a problem that includes complex biophysical aspects and social issues.

In terms of approach, most articles use qualitative methods. This approach is widely used to explore in-depth understanding of practices, perceptions, and social dynamics that influence fire management. Quantitative approaches are also very common, especially in articles that use statistical analysis and remote sensing to look at how fires spread or how well technology works to stop them. There is also one article that adopts a conceptual approach through a knowledge system approach, which aims to develop a cross-actor knowledge system to reduce fire risk.

Figure 4 is presented in the form of an Alluvial Sankey diagram, a type of flow diagram that visualizes how different categorical variables are connected or related. In this study, it is used to illustrate the relationship between research focuses (ecological or social) and the methodological approaches (qualitative, quantitative, or conceptual) adopted in each article. This visual representation helps to identify patterns and overlaps across thematic and methodological choices in the reviewed literature.

Qualitative approaches were widely used to explore local actors' perspectives through semi-structured interviews, field observations, and case studies. Several studies applied data triangulation to increase validity, such as combining interviews, literature reviews, and questionnaires (Puspitaloka et al., 2021; Yasir et al., 2023) or combining interviews

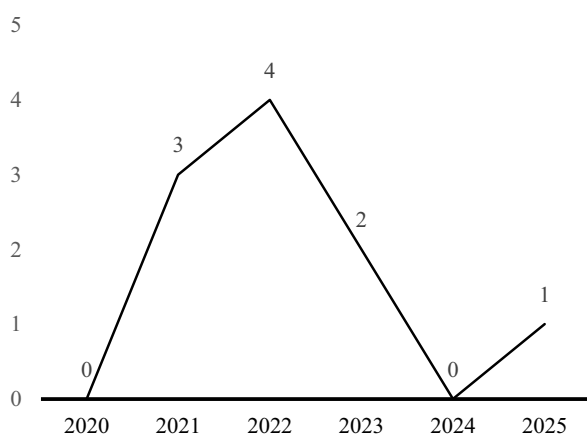


Figure 3 Trend of number of articles in different time period.

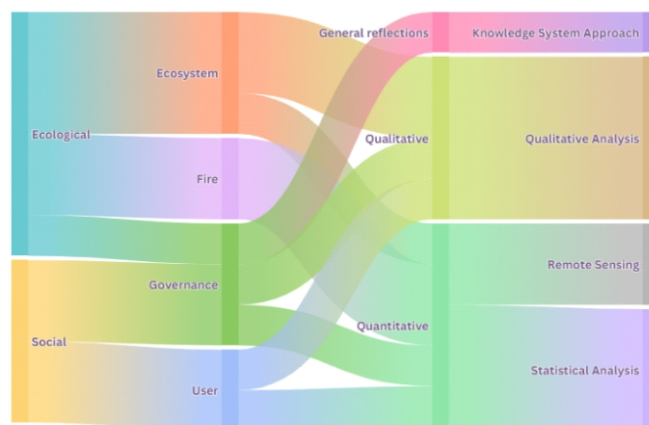


Figure 4 Alluvial Sankey diagram of focuses and method.

with observations of land cover conditions and wetting infrastructure (Usup et al., 2021). For quantitative approaches, several studies relied on spatial data and remote sensing technology, such as the use of MODIS and Landsat imagery to map fire hotspots and canal network (Imron et al., 2022; Sandhyavitri et al., 2023a). Evaluation of the effectiveness of artificial rain was also carried out through analysis of precipitation and hotspot data (Sandhyavitri et al., 2023a; 2023b). In addition, spatial linear programming was used to determine the priority of restoration areas based on ecological and economic benefits (Tan et al., 2022). Furthermore, one study used a two-stage qualitative comparative analysis (QCA) to understand the complex causal factors in successful fire reduction (Carmenta et al., 2021), while another applied a knowledge system approach to build a collaborative knowledge system across actors (Robins et al., 2022).

The diverse research methods reflect the multi-disciplinary approach carried out in the study of peatland management over a period of 5 years. Some articles rely on interviews and case studies, while others use spatial data, statistical analysis, or even weather modification technology. Approaches to the peatland fire issue continue to evolve, not only technically but also conceptually, as awareness of the importance of integrating social, ecological, and institutional aspects increases.

Content study: Socio-ecological dimensions in peat fire management This section outlines the socio-ecological content taken from the selected articles, highlighting the ideas presented by each study. The analysis in the Table 3 focuses on the socio-ecological concepts contained in peatland fire management in each study. Thus, this synthesis provides a clearer understanding of how socio-ecological dimensions are implemented in the context of peatland fire management in various cases.

Content study: Type of intervention and conclusions Table 4 is the basic ideas of the 10 articles analyzed, based on the actions and strategies proposed and what findings were obtained from the implementation of these. In addition, it is also equipped with the impact of the implementation, which has been achieved as a picture of the results.

Discussion

The 10 reviewed documents vary in their objectives, scope, and methodological approaches. Nevertheless, they all contribute to a shared understanding of the challenges and opportunities in addressing peatland fire management in Indonesia. Each study, in its own way, reflects the increasing recognition that this issue cannot be addressed through technical means alone and consistently points to the importance of integrating ecological, institutional, and socio-cultural dimensions.

To better synthesize these insights, this review draws on a loop framework (Figure 5) that illustrates the dynamic and reciprocal relationships between resource systems, governance systems, resource units, actors, and focal action situations.

In this loop, degraded peat ecosystems as a part of the resource systems aspect are both shaped by and have

influence over governance structures, which in turn regulate and empower actors, from local communities to institutions. Meanwhile, wildfires as the resource units directly affect peat conditions and catalyze interventions. Ultimately, all these elements converge in focal action situations such as rewetting initiatives, fire prevention programs, and the deployment of technology, which are co-determined by both actors and the environmental context. This recursive structure suggests that any effective intervention must close the loop by considering how each component influences and is influenced by the others.

While ecological interventions like rewetting and revegetation remain central, our review finds that their success hinges on the quality of governance and the depth of community engagement. Studies by Puspitaloka et al. (2021), Usup et al. (2021), and Yasir et al. (2023) affirm that programs are more effective and sustainable when local actors are involved. However, meaningful involvement remains elusive. As Carmenta et al. (2021) and Robins et al. (2022) caution, participation often stops at consultation and lacks genuine power-sharing. Without structural shifts toward decentralized decision-making, participatory initiatives risk becoming symbolic rather than transformative.

Equally critical is the role of hybrid governance models, involving cross-sectoral collaboration among government, NGOs, corporations through CSR, and communities (Wulandari et al., 2021; Tan et al., 2022; Yasir et al., 2023). These arrangements are often celebrated for their inclusiveness and responsiveness. Yet implementation remains inconsistent. For example, Wulandari et al. (2021) underscore the strength of local knowledge and social capital, while Imron et al. (2022) highlight enduring disconnects between national policies and localized realities. This suggests a persistent tension between centralized control and the diverse socio-cultural and ecological landscapes in which policies must operate.

Technological innovation, particularly weather modification technology (WMT), has gained traction as a tool to reduce fire incidence. Studies by Sandhyavitri et al. (2023a; 2023b) demonstrate statistically significant links between increased rainfall and reduced fires. However, very few studies assess the ecological sustainability, economic feasibility, or social legitimacy of such interventions. Technologies introduced without attention to local perceptions or integration with community-based knowledge risk being perceived as external impositions because they are scientifically valid yet socially detached.

Another critical weakness revealed across the literature is the absence of robust monitoring and evaluation frameworks. Despite the proliferation of pilot projects and innovations, most studies fail to articulate measurable indicators for assessing long-term outcomes. For example, while rewetting is widely promoted, there is limited discussion on benefit distribution, maintenance, or effectiveness over time. Additionally, common systemic challenges such as fragmented institutions, short-term funding cycles, and inadequate coordination are acknowledged but insufficiently examined. These observations are further synthesized in Table 5.

Table 5 and the loop framework both point to a critical insight that fire mitigation efforts often remain fragmented

Table 3 Findings of socio-ecological dimensions

Authorship	Socio-ecological dimensions
Puspitaloka et al. (2021)	The importance of integrating ecological techniques like rewetting with social strategies such as community engagement and hybrid governance. The ecological dimension is addressed through restoration actions targeting degraded peat ecosystems, while the social dimension emphasizes multi-actor collaboration, cost-benefit evaluation, and inclusive planning to increase community acceptance and program sustainability.
Wulandari et al. (2025)	The study discusses how fragmented restoration efforts across sectors reduce overall program effectiveness. It emphasizes hybrid governance and the role of NGOs, government, and local communities. Ecologically, it focuses on the need for integrated approaches that reflect the interdependence between environmental recovery and social-economic systems.
Imron et al. (2022)	Anthropogenic pressures such as deforestation, land conversion, and infrastructure are having intensified peat fires and degraded protected ecosystems. While it focuses more on the ecological consequences (fire, biodiversity loss, emissions), it also suggests that governance strategies have not kept pace with local realities, indicating a mismatch between top-down policy and on-the-ground conditions.
Usup et al. (2021)	Community-based fire management supported by ICCTF through canal blocking and deep well construction. It balances ecological goals (restoring hydrology and reducing fire spread) with social elements, such as strong local participation and the need for operational and financial support for fire brigades. The participatory governance approach empowers local actors in both planning and monitoring.
Yasir et al. (2023)	CSR programs bridge technical interventions (equipment, training) with social empowerment. It shows how communities, through MPA and local farmer groups, contribute to fire prevention and restoration. The ecological aspect focuses on peat protection, while governance involves both public-private partnerships and culturally adapted strategies that reflect local needs.
Carmenta et al. (2021)	The effectiveness of peat fire prevention must be context-specific and supported by hybrid governance involving multiple stakeholders. On the ecological side, it highlights the complexity of peat fire behavior and the role of early warning systems like the Fire Danger Rating System (FDRS). Socially, it discusses the need for stronger cross-sectoral coordination and the integration of community knowledge with scientific tools to enhance local ownership and improve intervention outcomes.
Robins et al. (2022)	Integrating the scientific approaches with local practices is importance to improve peatland restoration. Ecologically, it focuses on degraded peat restoration to support smallholder livelihoods. Socially, it critiques the disconnection between national policies and local realities and calls for a more transdisciplinary and holistic approach that combines social, economic, and ecological factors under a single management framework. Empowering communities is seen as central to increasing program relevance and resilience.
Tan et al. (2022)	The role of collaborative and hybrid governance in managing multifunctional tropical forest landscapes, including peatlands. Ecological concerns are addressed through conservation and sustainable use efforts, while the social dimension is represented by partnerships across government, local communities, and other stakeholders. This approach allows for adaptive and flexible resource management that responds to both environmental challenges and community needs.
Sandhyavitri et al. (2023a)	Weather Modification Technology (WMT) as a tool to mitigate drought and fire risks in peatland ecosystems. Ecologically, WMT addresses fire-prone conditions by enhancing rainfall and supporting peatland hydrology. Socially, it reflects how human innovation, and governance can respond to ecological component, such as weather patterns to design preventative interventions. This shows an adaptive governance approach, where technology is used as a bridge between ecological understanding and institutional action.
Sandhyavitri et al. (2023b)	WMT was used to reduce peat fires by increasing rainfall. The ecological part focuses on how more rain helped lower fire hotspots and burnt areas. On the social side, it shows how humans use science, data, and technology to respond to environmental risks. It reflects a form of governance where decisions are based on weather and ecosystem conditions.

Table 4 Strategy, action, and conclusions

Authorship	What do they act and the strategy to manage peat fires?	What conclusions do they draw?
Puspitaloka et al. (2021)	<ol style="list-style-type: none"> 1. The 4Rs approach through Rewetting, Revegetation, Restoration, and Reducing Fire 2. Involving local communities in restoration efforts and fire prevention. 3. Integrating public and private sector participation to create a green business model that supports long-term funding and effective governance for peatland restoration and fire management. 	<ol style="list-style-type: none"> 1. Peat restoration is adjusted to the socio-ecological conditions in each location. 2. The involvement and commitment of all parties (government, community, private sector) are very important. 3. Market-based approaches help fund and maintain the sustainability of restoration efforts. 4. Collaborative governance (hybrid governance) and green business models need to be developed.
Wulandari et al. (2025)	<ol style="list-style-type: none"> 1. Participatory management strategies with integrating local communities into restoration initiatives. 2. The government provides economic benefits through initiatives like agroforestry training and enhancing social capital. 	<ol style="list-style-type: none"> 1. Strong social networks are important, but not sufficient for successful peatland restoration. 2. A holistic approach is needed that combines social networks, awareness, economic incentives, and program effectiveness. 3. The government needs to involve communities in a participatory manner, considering local customs and habits. 4. Participatory assessment should be a priority.
Imron et al. (2022)	<ol style="list-style-type: none"> 1. Community education and awareness and strengthening the role of MPA in villages around conservation areas. 2. Provision of fire-safe zones within protected areas as a place of refuge for animals during fires. 3. Increasing the capacity of field officers and improving infrastructure in line with the increasing risk of fires. 	<ol style="list-style-type: none"> 1. Protected areas are not completely free from fire. Risk management needs to be extended to the surrounding areas. 2. Any plan to change the status of a protected area must consider the risk of fire. 3. The landscape around the conservation area is very influential. If the buffer area is unable to contain the spread of fire, the protected area remains threatened.
Usup et al. (2021)	<ol style="list-style-type: none"> 1. Community based peatland rehabilitation program contributes significantly to climate change mitigation in Indonesia. 2. MPA needs to find a financing scheme, either in the form of a productive business that can be managed by them or from other schemes. 3. Rewetting efforts need to be followed by revegetation in areas prone to fire. 	<ol style="list-style-type: none"> 1. Rewetting and fire prevention have been proven to be effective in significantly reducing CO₂eq emissions. 2. Community involvement as community fire brigades is important but is constrained by operational funds such as transportation and equipment maintenance. 3. Fire locations generally occur on degraded peatlands such as bushes, open areas, and agricultural land.
Yasir et al. (2023)	<p>The implementation separated to two types of actions:</p> <ol style="list-style-type: none"> 1. Activities action more like intensive focus group discussion, program synchronization, media broadcast, and training. 2. Infrastructure action more like build the rewetting supporting infrastructure and provide the firefighting equipment for MPA. 	<ol style="list-style-type: none"> 1. CSR contributes to peat fire mitigation through environmental communication and community empowerment. 2. Farmer community-based approaches are strengthened through training, group strengthening, and cross-party collaboration. 3. Communities are supported with fire extinguishers, training, and competitions, as well as building local capacity in fire prevention. 4. Communities acted as local communicators, drawing on cultural values.
Carmenta et al. (2021)	<ol style="list-style-type: none"> 1. Emphasize prevention efforts and resonate with local constituents, it will increase the legitimacy. Prevention is more important than incentives in ensuring fire-free outcomes. 2. Combined interventions are more effective than single approaches, especially in villages with high fire risk. 	<ol style="list-style-type: none"> 1. The “one-size-fits-all” approach is ineffective, as programs must be tailored to local conditions. 2. Fire mitigation programs need to consider contextual factors such as peatland scale, tenure status, and ethnic diversity. 3. The success of national-scale programs such as FFV (Fire-Free Village) depends on adaptation to local contexts and the availability of incentives

Table 4 Strategy, action, and conclusions (continued)

Authorship	What do they act and the strategy to manage peat fires?	What conclusions do they draw?
Robins et al. (2022)	Knowledge systems approach with 3 components: <ol style="list-style-type: none"> 1. Stakeholder mapping to understand stakeholder relationships and positions. 2. PCC (Policy Coordination Committee) to reach out to top-level policymakers. 3. SEF (Stakeholder Engagement Forum) to build shared understanding with mid-level stakeholders. 4. Developing the Peat FDRS (Fire Danger Rating System) which is recognized as a long-term platform for peat fire mitigation in Indonesia. 	<ol style="list-style-type: none"> 1. Coordination between institutions and cross-disciplinary researchers is lacking, due to minimal previous collaborative experience and technical limitations. 2. Policy dialogue as a space for deliberation between researchers and policy makers 3. The success of peat fire management is highly dependent on strengthening cross-institutional coordination and a shared understanding of the knowledge system.
Tan et al. (2022)	The study emphasizes the following actions and strategies to manage peat fires: <ol style="list-style-type: none"> 1. Rewetting Peatlands: Restoring water table levels to reduce the likelihood of fires. 2. Blocking Drainage Canals: Preventing water loss from peatlands, which helps maintain moisture and reduces fire risk. 3. Revegetation: Planting native peat swamp forest species to restore habitats and enhance ecosystem resilience. 4. Fire Mitigation: Implicitly integrated into restoration activities to prevent fire outbreaks and associated health risks. 	<ol style="list-style-type: none"> 1. Local conditions such as tenure, social, political, are crucial in determining restoration locations. 2. Land competition and national policies that do not support the program can hinder the implementation of restoration. 3. The model does not sufficiently consider socio-economic and legal factors that influence success in the field. 4. Peat restoration is a cheap and effective nature-based solution for climate mitigation and ecosystem recovery. 5. Spatial optimization with detailed local data is important to prioritize restoration sites effectively
Sandhyavritri et al. (2023a)	The implementation of Weather Modification Technology (WMT) to induce rainfall and reduce fire occurrences. Additionally, conventional methods such as using water from existing canals for direct water sprays during dry seasons.	<ol style="list-style-type: none"> 1. Water Management Techniques (WMT) has been proven to be effective in reducing carbon emissions, the number of hotspots, and burned areas in peatlands. 2. WMT also significantly increased rainfall during the observation period. 3. WMT is considered a successful engineering solution for peat fire mitigation.
Sandhyavritri et al. (2023b)	The implementation of Weather Modification Technology (WMT) to induce rainfall and reduce fire.	<ol style="list-style-type: none"> 1. The success indicator (Precipitation Change > 1) shows that the implementation of WMT is considered successful. 2. The correlation between increased precipitation and decreased hotspots is very strong (> 80%), supporting the effectiveness of WMT in fire mitigation.

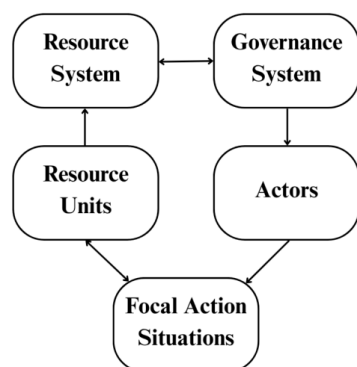


Figure 5 Loop framework of social-ecological approaches.

and fail to generate the feedback necessary for adaptive, system-based responses. While there is evident conceptual progress, this has not been matched by equally integrated operational strategies.

In conclusion, effective peatland fire management requires more than isolated technical fixes. It demands a systemic approach that embraces complexity, fosters cross-scale adaptive governance, enables genuine community empowerment, and integrates traditional knowledge with scientific tools. Future efforts should prioritize mechanisms that close the loop, ensuring interventions are continuously informed by social, ecological, and institutional feedback to foster resilience, legitimacy, and long-term success.

Table 5 Research gaps within the reviewed literature

Thematic aspect	Observed gap	Implication
Community engagement	Participation often remains consultative, not transformative	Limits power-sharing and long-term local ownership
Hybrid governance	Lack of institutional alignment between national policies and local realities	Reduces responsiveness to local socio-cultural contexts
Technological innovations	Limited assessment of long-term impacts, community perception, or equity	Risks low legitimacy and sustainability of interventions
Monitoring and evaluation	Absence of standardized indicators or long-term tracking	Hinders evidence-based policy refinement

Conclusion

This article presents a systematic literature review of ten selected scientific studies published between 2020 and 2025 that discuss strategies for mitigating peatland fires in Indonesia. The findings show that the most effective strategies are those that integrate technical measures with social strategies, particularly the active involvement of local communities. In addition, technological innovations like WMT and early warning systems are increasingly recognized for their role in supporting ecological restoration and fire prevention. Effective mitigation efforts are typically supported by collaborative and adaptive governance models that are responsive to socio-ecological conditions, including land tenure systems, cultural practices, actor dynamics, and institutional capacities. The involvement of the private sector through CSR programs and the empowerment of local institutions like MPA further strengthen community-based mitigation frameworks. However, this review also identifies key limitations in the current literature. Most studies do not provide insights into the long-term sustainability of interventions once external programs end, limiting the understanding of lasting impacts across social, ecological, and institutional domains. Additionally, few studies examine the interconnection between social, economic, and ecological factors holistically, despite acknowledging their importance. The local context, while often mentioned, remains under-analyzed as a critical variable influencing the success or failure of interventions.

Recommendation

The gaps indicate that peat fire mitigation should be approached as a complex socio-ecological challenge, not only a technical or policy issue. Future research should therefore adopt more evaluative, data-driven, and context-sensitive approaches that explicitly address how social systems and ecological processes interact in shaping sustainable fire mitigation outcomes.

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