

AI-Enhanced Remote Sensing for Forest Fire Mitigation: Integrating UAV and Satellite Imagery to Strengthen Indonesia's National Security

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Abstract

Forest fires pose a significant ecological and national security threat, with increasing frequency and intensity driven by both natural and anthropogenic factors. Remote sensing technology has emerged as a strategic solution for early detection and mitigation of forest fires in high-risk areas. This study employs a qualitative literature review method, analyzing more than 15 recent scholarly articles focusing on the use of satellite imagery, UAVs, and machine learning integration in fire monitoring systems. The data were examined to assess the effectiveness of remote sensing in prediction, active detection, and post-fire management. Findings indicate that remote sensing technology, especially those utilizing multispectral imagery and surface temperature sensors, can improve fire detection accuracy to over 90%. AI-based segmentation systems and UAV imagery have proven effective in accelerating real-time wildfire response. Additionally, spatial data contributes to mapping fire-prone zones and planning strategic mitigation efforts. In conclusion, the integrative use of remote sensing strengthens early warning systems and decision-making processes in forest fire management, while safeguarding ecosystem stability and national security.

Keywords:

Remote sensing; Forest fire; Early detection; UAV; AI; National security.

1. INTRODUCTION

Forest fires represent one of the most complex and multidimensional environmental hazards globally, with cascading consequences for biodiversity, atmospheric quality, agricultural productivity, and governance stability. In recent decades, both the frequency and severity of wildfire events have intensified, driven by synergistic interactions between climate change, land-use transformation, and anthropogenic pressures (Bedia et al., 2015; Rodrigues et al., 2020). Indonesia occupies a particularly precarious position within this global trend: as the world's third-largest tropical forest nation, its peatland and lowland forest ecosystems are highly susceptible to fire, especially during El Niño-driven drought events that periodically extend and intensify the fire season.

The ecological consequences of unchecked forest fires are well-documented. Fires alter vegetation composition and soil biochemistry increasing pH, electrical conductivity, and nitrogen levels while reducing organic carbon and potassium thereby degrading long-term ecosystem services (Dobhal et al., 2025). At the national scale, fires impose severe externalities through transboundary haze pollution, displacement of local communities, destruction of agricultural land, and disruption of food supply chains (Yan & Wang, 2022; Indra et al., 2023). In Indonesian provinces such as Riau, Kalimantan, and South Sumatra, recurring fire events have consistently overwhelmed the adaptive capacity of both local governance structures and conventional monitoring systems.

Remote sensing (RS) technology has emerged as a transformative tool in addressing these challenges. Satellite-based platforms including MODIS, ASTER, Landsat, and Sentinel-2 provide macro-scale, multi-

temporal fire monitoring capabilities, while unmanned aerial vehicles (UAVs) offer high-resolution, real-time surveillance at operational scales inaccessible to conventional satellite revisit cycles. The integration of artificial intelligence (AI) into RS pipelines through semantic segmentation, deep learning classifiers, and edge computing architectures has further elevated detection accuracy and reduced response latency in wildfire scenarios (Barmpoutis et al., 2023; Yu et al., 2024).

However, despite the proliferating literature on AI-enhanced remote sensing for wildfire management, several critical gaps persist. First, the majority of technically validated deployments have been conducted in temperate, Mediterranean, or East Asian contexts; tropical peatland and equatorial forest environments characteristic of Indonesia's most fire-prone landscapes remain empirically underrepresented. Second, existing reviews tend to treat RS applications descriptively, without systematically comparing the relative effectiveness of technologies across detection tasks (early detection versus area mapping versus predictive modeling) or synthesizing conflicting findings regarding model accuracy under varying environmental conditions. Third, the translation of technological capabilities into governance-ready policy recommendations for Indonesia's National Disaster Risk Reduction (BNPB) framework remains insufficiently developed in the literature.

This study addresses these gaps through a systematic literature review that evaluates the integration of AI-based remote sensing in forest fire mitigation, with an explicit analytical focus on: (a) the comparative effectiveness of technologies for early detection versus predictive modeling; (b) their applicability to Indonesia's tropical fire environments; and (c) their implications for national resilience governance. By moving beyond descriptive survey toward critical synthesis, this review aims to furnish an evidence base for researchers and policymakers engaged in strengthening Indonesia's fire monitoring and disaster governance infrastructure.

2. RESEARCH METHOD

This study employs a systematic qualitative literature review methodology to examine the effectiveness of remote sensing, UAV, and AI-based technologies in forest fire detection and mitigation, and to evaluate their policy implications for national resilience governance in Indonesia. The review protocol was designed in accordance with established systematic review principles, incorporating structured search strategies, explicit inclusion and exclusion criteria, and a transparent article selection process.

2.1. Database Search and Access

Literature searches were conducted across three primary academic databases: Scopus, Web of Science (WoS), and Google Scholar. All databases were accessed between January 15 and March 10, 2025. The following Boolean search string combinations were applied across title, abstract, and keyword fields:

("remote sensing" OR "satellite imagery" OR "UAV" OR "unmanned aerial vehicle") AND ("forest fire" OR "wildfire" OR "fire detection") AND ("artificial intelligence" OR "machine learning" OR "deep learning" OR "neural network")

Secondary search strings incorporated supplementary terms including: "fire mitigation," "hotspot monitoring," "burned area mapping," "fire prediction," "fire risk assessment," and "Indonesia" to capture contextually relevant literature from Southeast Asian and tropical forest contexts.

2.2. Inclusion and Exclusion Criteria

Articles were included if they: (1) were published in peer-reviewed journals between 2002 and 2025; (2) addressed remote sensing, UAV technology, or AI applications specifically in the context of forest or wildfire management; (3) reported empirical results, technological evaluations, or systematic analyses of fire detection or mitigation systems; and (4) were published in English or available in full English translation. Articles were excluded if they: (1) were conference abstracts, editorials, or short communications without full empirical reporting; (2) addressed agricultural fire, industrial combustion, or indoor fire scenarios unrelated to forest ecosystems; (3) were duplicate publications; or (4) were secondary news reports or non-peer-reviewed institutional documents.

2.3. Article Selection and Screening

An initial database search returned 287 candidate records across the three platforms (Scopus: 143; Web of Science: 98; Google Scholar: 46). After deduplication, 242 unique records were screened by title and abstract, yielding 42 articles for full-text review. Following full-text assessment against the inclusion and exclusion criteria, 10 articles were excluded due to insufficient empirical content (n=5), inaccessibility of full text (n=3), or topical mismatch (n=2). A final corpus of 32 peer-reviewed articles was retained for systematic analysis and synthesis. The article selection process is summarized in the simplified PRISMA-style flow presented in Table 1.

Table 1. Article Selection Flow (Simplified PRISMA Diagram)

Stage	Action	Records (n)
Identification	Database search: Scopus (143), Web of Science (98), Google Scholar (46)	287
Deduplication	Removal of duplicate records across databases	242
Screening	Title and abstract screening against inclusion/exclusion criteria	42
Eligibility	Full-text review; exclusions: insufficient content (5), inaccessibility (3), mismatch (2)	32
Included	Final corpus retained for systematic analysis and synthesis	32

2.4. Data Extraction and Synthesis

Data extraction followed a structured coding framework organized around four thematic categories: (1) technology platform (satellite, UAV, hybrid); (2) analytical function (early detection, burned area mapping, fire prediction, risk assessment); (3) geographic and ecological context; and (4) reported performance metrics and identified limitations. Synthesis employed an integrative review approach emphasizing comparative analysis, identification of conflicting findings, and explicit connection to Indonesian disaster governance priorities.

3. RESULTS AND DISCUSSION

This section synthesizes findings across the 32 reviewed studies into four analytically structured themes: (3.1) AI and UAV-based systems for early fire detection; (3.2) satellite remote sensing for macro-scale monitoring and predictive modeling; (3.3) fire drivers and contextual relevance to Indonesia; and (3.4) implications for national resilience governance. Where studies report conflicting findings or distinct performance characteristics, these are examined explicitly.

3.1. AI and UAV-Based Systems for Early Fire Detection: Comparative Effectiveness

Among the reviewed technologies, deep learning-based semantic segmentation and object detection models deployed on UAV platforms demonstrate the highest detection accuracy for early-stage fires. ADE-Net (Kong et al., 2024), an attention-based dual-encoding network incorporating dual semantic and spatial coding paths with multi-attention fusion (MAF), attention-guided enhancement (AGE), and global context fusion (GCF) modules, achieves superior segmentation performance compared to baseline models on standard remote sensing benchmarks. FireFormer (Tong et al., 2024), a CNN-Transformer hybrid combining ResNet18 encoding with a Forest Fire Transformer Block decoder, records 73.13% IoU and 84.48% F1 Score on the FLAME dataset under real-time constraints. A modified YOLOv8 architecture incorporating local convolution, EMA modules, and agent attention mechanisms (Zhu et al., 2025) achieves 93.57% precision and 88.51% recall in drone-deployed environments a substantial improvement of 5.05% precision and 2.72% recall over the original YOLOv8 baseline, alongside reductions in computational overhead of 14.3% FPS improvement and 25% GFLOP reduction.

Critically, performance comparisons across these studies are complicated by methodological heterogeneity: benchmark datasets differ (FLAME, SMOKE5K, custom datasets), environmental conditions vary substantially across geographic contexts, and reported metrics are not consistently standardized across studies. ADE-Net and the enhanced YOLOv8 model report the highest overall performance metrics in their respective benchmark evaluations; however, neither has been validated in tropical peatland environments representative of Indonesia's most fire-prone landscapes. This represents a significant limitation for direct transferability assessments.

Smoke detection presents a technically distinct challenge from flame detection, requiring different architectural approaches. The Forest Smoke-Fire Net (FSF Net) proposed by Ding et al. (2024) combines MODIS satellite imagery with dynamic brightness temperature thresholds and deep learning specifically, a Mask_RCNN_ResNet50_FPN and XGBoost ensemble achieving more accurate smoke detection than image-only approaches. Bhamra et al. (2023) similarly demonstrate that multimodal SmokeyNet, integrating satellite data, weather sensor readings, and optical camera feeds, detects wildfire smoke within minutes and outperforms single-sensor baselines. These findings consistently support the conclusion that sensor fusion architectures outperform single-modality detection systems a finding with direct architectural implications for the design of Indonesia's heterogeneous fire environment monitoring systems.

UAV-based thermal infrared video represents another operationally promising approach. Valero et al. (2021) demonstrate that software-based TIR video stabilization using KAZE feature matching achieves registration accuracy 10 to 1,000 times superior to conventional methods across nine real-fire video

recordings, enabling systematic analysis of fire spread behavior and real-time decision support. Mu et al. (2025) extend this approach through edge computing integration, achieving mAP of 93.76% at 34.6 FPS on standard hardware and 97.53% mAP at 16 FPS on iCrest edge devices — critically, without requiring real-time telecommunications connectivity. This edge computing capability is particularly relevant for Indonesia's frontier forest zones, where data connectivity is frequently unavailable or unreliable. In comparative synthesis, the most effective technologies for early fire detection identified in the reviewed literature are: (a) attention-based deep learning models deployed on UAV platforms (ADE-Net, YOLOv8 variants), offering the highest precision under controlled benchmark conditions; and (b) multimodal fusion architectures integrating multiple sensor streams (satellite, weather, optical), offering greater robustness under operationally complex and variable conditions. For Indonesia, where both technical performance and operational resilience are required, the multimodal edge-computing approach (Mu et al., 2025; Bhamra et al., 2023) appears most practically applicable in the near term.

3.2. Satellite Remote Sensing for Macro-Scale Monitoring and Predictive Modeling

Satellite-based remote sensing platforms occupy a complementary but functionally distinct role relative to UAV systems: rather than providing high-resolution real-time detection, they enable landscape-scale fire mapping, historical analysis, and predictive risk modeling at spatial extents unreachable by any UAV system. Yu et al. (2024) demonstrate that combining MODIS-derived Nighttime Lights (NTL) data with Random Forest classifiers achieves over 92% classification accuracy for forest fire pixels and more than 99% user accuracy in Southwest China performance directly attributable to the multi-source data integration strategy rather than satellite imagery alone. ASTER, operating at 30-meter spatial resolution, permits spatially resolved active fire characterization; Giglio et al. (2008) report detection rates of 0.8 to 0.9 with low false alarm rates across diverse geographic contexts, positioning ASTER as a calibration reference for coarser satellite fire products.

Predictive modeling represents one of the most consequential satellite data applications. Jo et al. (2023) demonstrate that integrating satellite-derived land surface temperature, soil moisture, and vegetation indices into the FLAM fire model improves predictive correlation from $r = 0.171$ to $r = 0.893$ a transformative performance gain that validates multi-source satellite data integration for fire likelihood forecasting. Roh et al. (2024) report that their machine learning-based diagnostic model for South Korea correctly identifies 73% of recorded fire incidents as high-risk events. The substantial performance gap between these two models likely reflects differences in predictor variable specificity, model architecture, and the training data volume available in each geographic context, suggesting that model performance is highly context-dependent and that results from South Korea cannot be directly extrapolated to Indonesia without retraining.

A particularly instructive comparative finding emerges from data-scarce contexts. In Lebanon, Majdalani et al. (2022) use VIIRS and MODIS data to reconstruct a two-decade fire regime record, revealing bimodal seasonal fire peaks (July and November) invisible in official statistics. In Tunisia, Belhadj-Khedher et al. (2018) demonstrate that Landsat-based burned area estimation corrects official fire records by approximately 77% (from a stated 1,017 ha/year to an estimated 1,799 ha/year), underscoring the severity of documentation gaps in fire-prone regions. Indonesia faces directly analogous challenges: BNPB and regional BPBD agencies have documented difficulties in consistent fire incident reporting across Kalimantan and Sumatra, suggesting that satellite-based fire record validation would yield comparably significant improvements in risk modeling input quality.

For spatial vulnerability assessment, Novkovic et al. (2021) demonstrate Sentinel-2 imagery combined with Random Forest models can identify high-risk fire zones incorporating fuel load, topography, and meteorological predictors. Talukdar et al. (2024) apply multispectral satellite imagery to project that temperature increases of up to 3°C would substantially expand fire-prone zones in northeastern India — a finding directly transferable to Indonesian provincial-scale climate adaptation planning. Marnain et al. (2023) further show that fuzzy integration of multi-sensor satellite data improves burned area extraction accuracy for Himalayan forests. Across these studies, a consistent finding emerges: the integration of multiple satellite data streams (thermal, optical, radar) systematically outperforms single-sensor approaches in both detection accuracy and spatial coverage completeness.

3.3. Fire Drivers, Ecological Vulnerability, and Relevance to Indonesia

A cross-study synthesis reveals that forest fires are driven by two interacting factor categories biophysical and anthropogenic whose relative influence varies by region, with important implications for monitoring system design. Understanding this interaction is essential for designing contextually effective RS systems. Among biophysical drivers, drought and extreme temperature events consistently emerge as primary accelerants of fire occurrence. Rodrigues et al. (2020) identify four dominant fire weather typologies in the Iberian Peninsula, with heat-wave-driven and seasonal-drought-driven fires exhibiting distinct spatial patterns requiring differentiated early warning approaches. Bedia et al. (2015) establish that boreal forests and humid tropical broadleaf forests the ecosystem type most analogous to Indonesian peatland forests exhibit the highest sensitivity to interannual fire weather variability among global biomes, and project significant future increases under CMIP5 scenarios. A critical limitation in applying these biophysical models

to Indonesia, however, is that most fire weather indices were calibrated on temperate surface fire dynamics; peatland subsurface combustion the dominant fire type in Kalimantan and Sumatra exhibits fundamentally different moisture retention, ignition thresholds, and propagation behavior, potentially rendering standard fire weather index thresholds unreliable for operational early warning.

Anthropogenic drivers are comparably influential across all reviewed geographic contexts. Saladyga et al. (2024) demonstrate that fire frequency in Appalachian pine forests closely tracked industrial activity patterns, with coal production peaks associated with the most extensive fire periods. Ganteaume et al. (2013) establish that the majority of Mediterranean European fires are human-caused, with fire occurrence density strongly correlated with population proximity and seasonal human activity patterns. The Indonesian case exhibits both dimensions simultaneously: Indra et al. (2023) document that recurrent fires in Riau Province persist despite successive governance interventions, attributing persistence to weak inter-agency coordination, legally unresponsive regulatory frameworks, and discriminatory enforcement practices that systematically disadvantage smallholder communities while enabling plantation-sector burning. This governance fragmentation cannot be resolved through technological means alone it requires coordinated institutional reform alongside RS system deployment.

Etten's (2023) documentation of fire-exacerbated ecosystem degradation in Baluran National Park, East Java, provides a directly relevant Indonesian case: recurrent anthropogenic fire creates a self-reinforcing degradation cycle in which fire-tolerant invasive species (*Acacia nilotica*) displace native dry tropical forest species, increasing landscape flammability and vulnerability to subsequent fire events. This feedback dynamic implies that RS-based fire monitoring systems for Indonesia must integrate ecological trajectory monitoring not merely hotspot detection to support management decisions that address the root causes of recurrent burning.

3.4. Implications for National Resilience Governance and Policy Recommendations

The reviewed literature, synthesized across technical and contextual dimensions, generates four cross-cutting policy-relevant findings for Indonesia's forest fire governance framework. First, Indonesia's current BNPB early warning architecture, which primarily relies on MODIS hotspot data accessed through the LAPAN Fire Hotspot Monitoring System, faces documented resolution limitations: MODIS's approximately 1-km spatial resolution results in systematic under-detection of small or early-stage fires, particularly in fragmented peatland margins and mixed-use forest boundaries where fire ignition commonly occurs. The reviewed evidence supports integrating Sentinel-2 imagery (10-meter resolution) for operational vulnerability mapping, UAV-based supplementary surveillance for high-risk zone monitoring during peak fire seasons (July–October), and ASTER data as a validation reference for area estimation consistent with the multi-source integration approach demonstrated by Yu et al. (2024) and Talukdar et al. (2024).

Second, AI model operationalization requires governance-level consideration beyond technical performance. Deployment contexts in Indonesia characterized by limited telecommunications infrastructure in frontier forest zones, persistent cloud cover that reduces satellite optical revisit effectiveness, and institutional capacity constraints at provincial BPBD level differ substantially from the laboratory and controlled-field conditions under which reviewed models were validated. Edge computing UAV platforms (Mu et al., 2025) offer a partial solution by reducing real-time data connectivity dependence; however, their sustained deployment requires dedicated funding mechanisms, operator training programs, and fleet maintenance protocols that current BNPB operational budgets do not routinely provision.

Third, the food security and socioeconomic threat dimensions documented in the reviewed literature particularly the role of upstream forest integrity in sustaining downstream agricultural water cycles (Yan & Wang, 2022) reinforce the case for embedding forest fire governance within Indonesia's comprehensive national resilience framework rather than treating it as a standalone environmental or disaster management issue. Fires that degrade peatland and riparian forest functions simultaneously impair agricultural water availability, community livelihoods, and regional economic stability across multi-year recovery periods.

Fourth, the governance fragmentation documented by Indra et al. (2023) for Riau Province where overlapping jurisdictions between BNPB, KLHK (Ministry of Environment and Forestry), BPBD, and regional plantation licensing authorities create regulatory gaps represents a systemic constraint that technological investment cannot overcome independently. Policy coordination mechanisms, including standardized inter-agency fire incident reporting protocols, centralized spatial data sharing platforms, and legally mandated response time standards for high-risk zone detections, are prerequisite conditions for remote sensing technology to fulfill its early warning potential.

Based on this synthesis, four specific policy recommendations are advanced for Indonesia's forest fire governance: (1) Establish a multi-source sentinel fire monitoring platform integrating MODIS, Sentinel-2, and UAV data streams within BNPB's National Disaster Information Center (BNPB-PUSINFONAS), with interoperable regional BPBD access nodes; (2) Commission Indonesian tropical and peatland fire imagery datasets for AI model retraining and field validation, prioritizing Kalimantan and South Sumatra peat ecosystems; (3) Codify inter-agency data-sharing and operational response protocols between BNPB, KLHK, and regional governments through Presidential Regulation, addressing the coordination failures identified by Indra et al. (2023); and (4) Integrate remote sensing-derived fire risk indicators into Indonesia's National

Disaster Risk Index as mandatory operational monitoring components tied to provincial disaster preparedness budget allocations.

Table 2. Overview of Reviewed Technologies: Functions, Performance, and Applicability to Indonesia

Technology	Primary Function	Representative Performance	Key Study	Indonesia Applicability
UAV + DL (ADE-Net)	Early fire/flame detection	Superior to baseline on benchmark datasets	Kong et al. (2024)	High pending tropical validation
UAV + YOLOv8	Real-time flame & smoke detection	93.57% precision; 88.51% recall	Zhu et al. (2025)	High suitable for frontier zones
UAV + Edge Computing	Real-time fire detection without connectivity	97.53% mAP on public dataset	Mu et al. (2025)	Very High addresses connectivity constraints
MODIS + Random Forest	Landscape-scale fire classification	>92% classification accuracy	Yu et al. (2024)	High LAPAN already uses MODIS data
Sentinel-2 + RF	Vulnerability zone mapping	High-risk zone identification validated	Novkovic et al. (2021)	High 10m resolution; cloud-penetrating SAR option
FLAM Model + Satellite	Fire occurrence prediction	r improved from 0.171 to 0.893	Jo et al. (2023)	Moderate requires local model retraining
Multimodal Fusion (SmokeyNet)	Smoke detection & early warning	Minutes-scale detection time; best multimodal performance	Bhamra et al. (2023)	High robustness suits heterogeneous environments
ASTER (30m)	Active fire characterization & validation	Detection rate 0.8–0.9; low false alarms	Giglio et al. (2008)	Moderate limited revisit frequency

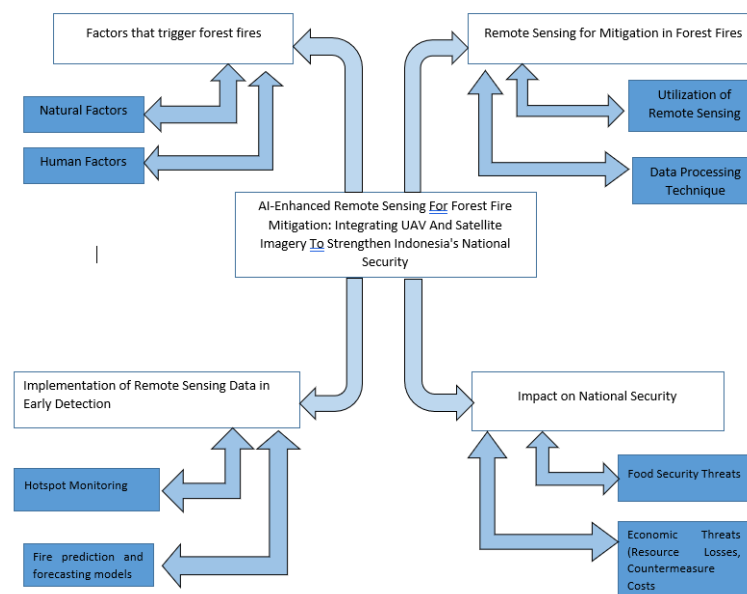


Figure 1. Brainstorming

This figure summarizes the relationship between the causes of forest fires, the use of AI-based remote sensing technology, and their impact on national security. This diagram is used to help readers understand how early fire detection and modeling using UAVs and satellite imagery contribute to mitigating risks to food security and economic stability.

4. CONCLUSION

This systematic literature review synthesizes evidence from 32 peer-reviewed studies to evaluate the state of AI-integrated remote sensing for forest fire detection and mitigation, with analytical focus on the Indonesian context. The findings demonstrate that AI-based detection architectures particularly attention-based deep learning models and multimodal fusion systems deployed on UAV platforms consistently achieve fire detection accuracies exceeding 90% under benchmark conditions, establishing them as technically superior to conventional satellite-only monitoring for early-stage fire identification. Satellite platforms, meanwhile, retain critical advantages for landscape-scale burned area mapping, historical fire regime analysis, and multi-year predictive modeling tasks that UAV systems cannot replicate at operational scale.

Critically, the reviewed literature reveals a persistent gap between technical performance under benchmark conditions and validated operational performance in Indonesia's tropical peatland and equatorial forest environments. The convergence of biophysical fire susceptibility — driven by El Niño-linked drought cycles and expanding fire weather conditions — and structural governance fragmentation in Indonesia suggests that technological capability alone is insufficient; contextually adapted governance integration is equally essential for effective fire mitigation.

The comparative analysis identifies edge computing UAV platforms and multimodal sensor fusion architectures as the most practically applicable technologies for Indonesia in the near term, given their resilience to connectivity constraints and operational variability. Satellite platforms, particularly Sentinel-2, offer the most scalable complementary capability for provincial-level vulnerability mapping and monitoring. The most urgently needed policy action is the establishment of standardized inter-agency data-sharing and coordinated response protocols that enable these technological capabilities to be operationally deployed within Indonesia's disaster governance infrastructure. Future research should prioritize: (1) empirical validation of AI-based detection systems in Indonesian peatland and tropical lowland forest field conditions; (2) development of Indonesian-specific fire imagery training datasets for deep learning model retraining; (3) comparative assessment of UAV deployment strategies across Kalimantan and Sumatra's heterogeneous fire landscapes; and (4) policy-embedded risk modeling frameworks that connect remote sensing outputs directly to BNPB operational decision-making cycles. Addressing these priorities will be essential for realizing the national resilience benefits that remote sensing technology, at its current level of technical maturity, is capable of delivering.

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