Satellite-Based Rainfall Thresholds for Landslide Initiation in Indonesia: A Systematic Literature Review

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Abstract
Rainfall thresholds are widely recognized as a key element in landslide early warning systems, as they help identify rainfall conditions under which slope failure is likely to occur. In Indonesia, the need to develop reliable rainfall thresholds is particularly urgent, given the high frequency of landslide events, the country's highly diverse physiographic characteristics, and the uneven distribution of rain gauges across many landslide-prone areas. At the same time, recent advances in satellite precipitation products, including IMERG, GSMaP, PERSIANN, and CMORPH, provide new opportunities to develop rainfall thresholds using datasets with broader spatial coverage. This study employs a qualitative approach through a Systematic Literature Review (SLR) to examine the evolution of satellite-based rainfall threshold research for landslide initiation in Indonesia. Relevant studies were systematically selected following the PRISMA 2020 framework. The selected literature was then extracted and analyzed using thematic synthesis, with particular attention to study context, satellite precipitation products, threshold formulations, validation approaches, and their potential application in landslide early warning systems. The synthesis identifies five major patterns. First, research in Indonesia has gradually shifted from the use of a single national rainfall threshold toward more localized and dynamic threshold models. Second, satellite precipitation data have become increasingly important as an alternative data source for areas with limited ground-based observations. Third, the performance of satellite precipitation products is highly context-dependent, varying across regions, spatial and temporal resolutions, and validation procedures. Fourth, the Bali/Badung research cluster reflects a more advanced methodological trajectory, as shown by the evaluation of gridded rainfall datasets, high-resolution datasets, double-fusion datasets, and comparative assessments between IMERG and MSWEP. Fifth, the main challenge is no longer merely to establish rainfall thresholds, but to translate them into early warning systems that are both scientifically robust and operationally practical. This study concludes that satellite-based rainfall thresholds for landslide initiation in Indonesia should be developed in a context-specific manner, validated using local evidence, and oriented toward multi-level warning system designs that can bridge scientific accuracy with institutional usability.

Keywords: rainfall thresholds; satellite precipitation; landslide early warning systems; PRISMA 2020; Indonesia

1 Introduction

Landslides are among the most critical hazards in Indonesia, as they are commonly triggered by the interaction of steep slopes, weathered materials, land-use changes, and intense or prolonged rainfall. At the global scale, Asia has been reported as the region with the highest proportion of landslide disaster occurrences. Recent studies in the ASEAN context also identify Indonesia as one of the countries with a prominent number of geological landslide events, where critical rainfall thresholds should be interpreted contextually rather than applied uniformly across regions (Gonzalez et al., 2024; Lu et al., 2024).

Within disaster mitigation frameworks, rainfall remains one of the most operationally relevant triggering factors because it can be monitored in near real time. For this reason, the concept of rainfall thresholds has become a key foundation of landslide early warning systems. Recent reviews indicate that rainfall thresholds have developed into one of the dominant approaches for reducing landslide risk. However, their performance is strongly influenced by how rainfall events are defined, the quality of landslide inventories, data resolution, time-series length, and the methods used to derive the thresholds (Gonzalez et al., 2024; Segoni et al., 2018).

The challenge is that rainfall threshold determination is never entirely neutral or universal. Current literature shows that research on landslide thresholds has grown rapidly, yet several recurring methodological limitations remain. These include issues related to the temporal scale of rainfall data, rain gauge density, rainfall accumulation criteria, and the insufficient integration of geological and geotechnical conditions into threshold classification (Gonzalez et al., 2024). This suggests that a threshold is not merely an empirical value that can be transferred from one region to another, but rather a methodological construct that is sensitive to physical context, data quality, and the intended purpose of its application.

In Indonesia, this issue becomes even more complex due to the country's highly diverse topography, geology, climate, and availability of ground-based rainfall data. A threshold revision study for the Indonesian Landslide Early Warning System (ILEWS) showed that the use of a single national rainfall threshold may reduce prediction accuracy, highlighting the need for updates based on actual landslide events and antecedent rainfall conditions (Yuniawan et al., 2022). This finding is consistent with a study in the Progo Catchment, Java, which demonstrated that dynamic thresholds using adaptive rainfall windows are more representative for early warning purposes than fixed-duration approaches (Satyaningsih et al., 2023).

At this point, the use of satellite rainfall products becomes increasingly strategic. Many landslide-prone areas in Indonesia are located in mountainous regions or in areas where rain gauge networks are sparse and inconsistent. Satellite products such as IMERG, GSMaP, PERSIANN, and CMORPH provide precipitation estimates with broad spatial coverage and frequent updates, making them highly promising for supporting early warning systems in areas with limited ground-based instrumentation. However, international literature has shown that the quality of satellite precipitation products is not uniform. Evaluations across mountainous and tropical regions indicate that the performance of IMERG, GSMaP, and other products varies depending on rainfall regime, temporal scale, topography, and application requirements (Maghsood et al., 2019; Marc et al., 2022; Rojas et al., 2021; Yu et al., 2021).

Evidence from Indonesia supports this argument. Evaluations of IMERG over the Indonesian Maritime Continent have shown reasonably good correlations at monthly and annual scales, although its performance tends to decline at finer temporal resolutions. An initial assessment of GSMaP version 08 in the same region also indicates strong potential for application, while still emphasizing the importance of validation against rain gauge observations (Ramadhan et al., 2022, 2023). This means that before satellite rainfall data are used to develop landslide thresholds, the quality and behavior of these products in the Indonesian context must first be carefully understood.

Similar findings have also emerged from satellite-based threshold studies outside Indonesia. A study in Rwanda demonstrated that satellite-derived hydro-meteorological information can be used to establish landslide initiation thresholds in data-scarce regions (Uwihirwe et al., 2022). Global systems such as LHASA further show that the integration of satellite data and precipitation forecasts can support hazard assessment and situational awareness over broad spatial scales (Khan et al., 2022). Taken together, these findings reinforce the view that satellite rainfall data offer significant opportunities, but they are not an automatic solution. Their use requires a critical synthesis of context, methodology, and limitations.

To date, however, the literature on satellite-based rainfall thresholds for landslide initiation in Indonesia remains relatively fragmented. Some studies focus on revising operational thresholds, others develop dynamic thresholds at the watershed scale, while another group evaluates the performance of satellite precipitation products. Few studies have systematically addressed the key questions together: which datasets are most frequently used, which threshold models are dominant, how validation is conducted, and to what extent the results are relevant for landslide early warning systems. Meanwhile, international reviews suggest that threshold research continues to evolve, while highly vulnerable regions often remain underrepresented in broader syntheses (Gonzalez et al., 2024). This gap highlights the importance of conducting a Systematic Literature Review specifically focused on Indonesia.

Based on this background, the present study aims to systematically synthesize the development of satellite-based rainfall threshold studies for landslide initiation in Indonesia. The review focuses on the types of satellite data used, the threshold approaches developed, the validation strategies applied, and their implications for landslide early warning systems. Theoretically, this study seeks to clarify the paradigm shift from uniform rainfall thresholds toward more local and dynamic threshold approaches. Practically, it is expected to provide a stronger academic basis for developing more context-sensitive rainfall-based landslide early warning systems in Indonesia.

2 Research Methods

This study adopted a qualitative approach using a Systematic Literature Review (SLR) design. This design was considered appropriate because the purpose of the study was not to calculate a new rainfall threshold numerically, but to identify, evaluate, and synthesize existing scientific knowledge on satellite-based rainfall thresholds for landslide occurrence in Indonesia. To ensure transparency in reporting, the review was guided by the PRISMA 2020 framework (Page et al., 2021) and further strengthened by the ENTREQ principles for qualitative evidence synthesis (Tong et al., 2012).

The data sources consisted of international journal articles, nationally published articles indexed in international databases, academic conference proceedings, and other credible scientific sources that were substantively relevant to the topic. The literature search was conducted through major academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. The review focused on publications from 2020 to 2026, with priority given to studies published within the last five years to ensure that the synthesis remains current and reflects recent developments in the field.

The search strategy used a combination of keywords, including "landslide rainfall threshold," "rainfall-induced landslide," "satellite rainfall," "satellite precipitation," "IMERG," "GSMaP," "PERSIANN," "CMORPH," "Indonesia," and "landslide early warning system." These terms were selected because studies on rainfall thresholds may appear under different terminologies, such as intensity–duration thresholds, event–duration thresholds, antecedent rainfall, dynamic rainfall thresholds, or the evaluation of satellite precipitation products for warning applications.

The inclusion criteria covered studies that examined the relationship between rainfall and landslides, used or evaluated satellite-based rainfall data, had substantive relevance to Indonesia, and provided sufficiently clear methods for data extraction. The exclusion criteria included studies that discussed landslides without considering rainfall variables, precipitation studies with no direct link to landslide occurrence, opinion-based or non-scientific articles, and duplicate publications.

The study selection process was conducted in several stages: identification, deduplication, title and abstract screening, full-text eligibility assessment, and final inclusion. During the eligibility assessment, priority was given to studies that clearly described the type of satellite product used, spatial and temporal resolution, threshold formulation, study location, and performance metrics. To strengthen the methodological quality of the review, the critical appraisal process was also informed by the principles of AMSTAR 2, particularly regarding the clarity of the review question, traceability of the search strategy, justification for exclusions, and transparency of the synthesis process (Shea et al., 2017).

Data extraction was carried out using an analytical matrix that included the author and year of publication, study location, research objective, type of rainfall data, satellite product, data resolution, threshold form, validation strategy, main findings, and study limitations. These variables were selected because they are among the most important elements in interpreting rainfall-threshold results. Previous studies in both Indonesia and other countries have shown that threshold performance may vary considerably depending on the satellite product used, the temporal scale of rainfall, and whether bias-correction procedures are applied.

The extracted data were then analyzed using qualitative thematic analysis. The analytical process involved repeated reading, open coding, code grouping, category development, and the formulation of key synthesis themes. Based on the initial reading of the literature corpus, several major themes emerged, including the shift from national-scale thresholds toward local and dynamic thresholds, the competition and complementarity among satellite precipitation products, variations in threshold-development methods, and the challenges of implementing rainfall thresholds in Indonesia's landslide early warning systems.

The trustworthiness of the review was maintained through four strategies. First, credibility was supported by the use of multiple databases and explicit selection criteria. Second, dependability was ensured through an audit trail of the search process, selection tables, and the data extraction matrix. Third, confirmability was maintained by clearly distinguishing between findings reported in the source articles and the researcher's interpretation. Fourth, transferability was strengthened by providing clear contextual descriptions of each study, particularly regarding study location, satellite data type, and threshold formulation.

From an ethical perspective, this study relied exclusively on published scientific documents and therefore did not involve human participants directly. Nevertheless, academic integrity was maintained through accurate citation practices, balanced reporting of findings, and efforts to minimize selection bias throughout the review process.

3 Theoretical Framework

The theoretical foundation of this article is developed through three main conceptual lenses: the theory of rainfall thresholds for landslide initiation, the theory of satellite rainfall representation and measurement uncertainty, and the framework of landslide early warning systems as operational socio-technical systems. These three perspectives are used because they collectively explain how rainfall is conceptualized as a landslide-triggering factor, how satellite-based products represent rainfall, and how rainfall thresholds are translated into early warning decisions (Gonzalez et al., 2024; Uwihirwe et al., 2022).

First, the theory of rainfall thresholds for landslide initiation is based on the premise that rainfall-induced landslides tend to occur when a certain combination of rainfall intensity, duration, accumulation, or antecedent moisture exceeds the critical condition of a slope. Within this perspective, rainfall is not treated as the sole cause of landslides. Rather, it is understood as the immediate triggering factor acting upon slopes that already possess specific geological, geomorphological, and hydrological susceptibilities. This theoretical perspective has evolved into several threshold approaches, including intensity–duration thresholds, event–duration thresholds, cumulative rainfall thresholds, and models that incorporate antecedent rainfall conditions (Ebrahim et al., 2025; Segoni et al., 2018).

Second, the theory of satellite rainfall representation and measurement uncertainty emphasizes that satellite-based rainfall data do not measure surface rainfall in the same way as ground-based rain gauges. Instead, satellite products estimate precipitation through algorithms, sensor integration, spatial interpolation, and, in some cases, gauge-based bias correction. Consequently, rainfall values derived from satellite products should be understood as processed representations of atmospheric phenomena rather than direct observations that are free from bias. Recent studies have shown that the performance of satellite precipitation products such as IMERG, GSMaP, PERSIANN, and CMORPH varies across regions, temporal scales, and precipitation characteristics (Marc et al., 2022; Ramadhan et al., 2022, 2023; Rojas et al., 2021; Yu et al., 2021).

Third, the landslide early warning system framework views thresholds not merely as scientific artefacts, but also as decision-making instruments embedded within a broader system involving data, models, institutions, operators, and communities receiving warnings. From this perspective, a reliable threshold should not only demonstrate statistical accuracy but also be compatible with warning-level structures, acceptable false-alarm tolerance, operational simplicity, and institutional requirements (Khan et al., 2021, 2022; Liu et al., 2024).

When compared, the theory of rainfall thresholds for landslide initiation provides the strongest basis for explaining the physical triggering mechanism of rainfall-induced landslides. The theory of satellite rainfall representation and measurement uncertainty adds analytical depth by questioning whether the rainfall input used in threshold development is sufficiently representative of actual rainfall conditions. Meanwhile, the early warning system framework shifts the focus from a purely academic question to an operational one: whether the resulting threshold is reliable, interpretable, and simple enough to support real-world decision-making.

In this study, the theory of rainfall thresholds for landslide initiation is positioned as the core analytical lens, while satellite rainfall representation and early warning system perspectives serve as complementary lenses. This combination is important because the article does not merely examine whether rainfall thresholds have been developed, but also how they have been constructed, how reliable the underlying rainfall inputs are, and to what extent the resulting thresholds are relevant for landslide early warning systems in Indonesia. A robust threshold is not merely one that achieves high accuracy, but one that can effectively manage the trade-off between missed events and false alarms. In the Indonesian context, this issue is particularly important because the design of a landslide warning system must account for regional heterogeneity, data quality, and implementation capacity (Peng & Wu, 2024).

Based on these three conceptual lenses, the analytical framework of this study is built on the assumption that knowledge of satellite-based rainfall thresholds for landslides in Indonesia is shaped by the interaction between how researchers conceptualize rainfall as a landslide trigger, how satellite precipitation products represent that rainfall, and how thresholds are translated into the operational needs of early warning systems. Since this study adopts a qualitative SLR approach, the reviewed literature is not interpreted merely as a collection of numerical threshold values, but as a body of scientific narratives that reflects methodological choices, data assumptions, validation logic, and application-oriented considerations.

4 Results

The results section of this SLR is organized around the logic of evidence synthesis rather than the conventional reporting of primary field data. Following the screening process, which focused on studies related to Indonesia, landslides, rainfall thresholds, and satellite-based rainfall data, the core review corpus comprised seven major publications published between 2021 and 2025 (Figure 1): (Muntohar et al., 2021), (Yuniawan et al., 2022), (Satyaningsih et al., 2023), (Aryastana, Dewi, & Wahyuni, 2024a), (Aryastana, Dewi, & Wahyuni, 2024b), (Aryastana, Dewi, Wahyuni, et al., 2024), (Aina et al., 2025).

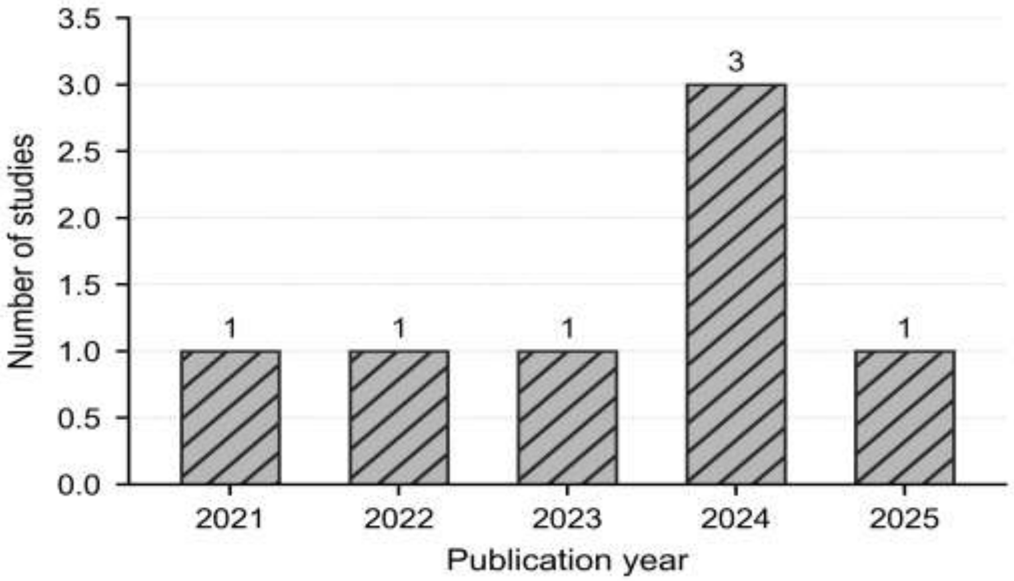

Figure 1. Annual distribution of reviewed studies on satellite-based rainfall thresholds for landslide initiation in Indonesia, 2021–2025.

Figure 1 shows that the number of publications remains limited, but it also reveals a clear upward trend, reaching a temporary peak in 2024. This pattern suggests that research on satellite-based landslide rainfall thresholds in Indonesia is moving beyond the initial proof-of-concept stage toward more robust methodological development and performance evaluation.

4.1 General Characteristics of the Included Studies

The identified corpus indicates that research on satellite-based rainfall thresholds for landslide initiation in Indonesia remains limited in volume but is steadily expanding. In its early phase, studies largely relied on TRMM data to support the development of a national landslide early warning system (LEWS). Subsequent research has shifted toward the use of more recent satellite precipitation products, including GPM, GSMaP, CMORPH, IMERG, and PERSIANN. Most of the available studies are framed as local or subnational case studies, with Java and Bali emerging as the dominant study regions (Table 1).

Table 1. Characteristics of the Included Studies

Study	**Study Area**	**Main Satellite Product**	**Threshold Approach**	**Summary of Findings**
(Muntohar et al., 2021)	Indonesia	TRMM	Empirical I–D threshold	The study derived the equation $I = 7.83D$^-0.328 for rainfall durations of 2–18 days. Although the model showed acceptable accuracy, the associated error remained relatively high.
(Yuniawan et al., 2022)	Java / ILEWS	GPM	1-day and 3-day effective antecedent rainfall	The revision of the national threshold improved predictive accuracy compared with using a single rainfall threshold for all of Indonesia.
(Satyaningsih et al., 2023)	Progo Catchment, Java	GSMaP-GNRT, CMORPH-CRT	Probabilistic dynamic event threshold	The GSMaP-based threshold achieved an AUC of 0.73, which was comparable to the rain-gauge-based threshold with an AUC of 0.72 and higher than the CMORPH-based threshold with an AUC of 0.64.
(Aryastana, Dewi, & Wahyuni, 2024a)	Badung, Bali	IMERG, PERSIANN	3-, 7-, 15-, and 30-day cumulative rainfall thresholds	The integration of rainfall datasets produced the best performance, with the highest AUC of 0.903 obtained for the 30-day cumulative rainfall threshold.
(Aryastana, Dewi, & Wahyuni, 2024b)	Badung, Bali	High-resolution satellite rainfall datasets	Rainfall-duration and cumulative rainfall comparison	The 15-day rainfall accumulation produced the highest AUC, exceeding 0.75.
(Aryastana, Dewi, Wahyuni, et al., 2024)	Badung, Bali	Dual-fusion satellite rainfall datasets	5-, 7-, 10-, and 15-day cumulative rainfall thresholds	The second-fusion dataset achieved an AUC of 0.82 for the 15-day cumulative rainfall threshold.
(Aina et al., 2025)	Metro Catchment, Indonesia	GSMaP NRT, PERSIANN CCS	Hourly I–D threshold with bias correction	GSMaP NRT outperformed PERSIANN CCS, while the 24-h no-rain gap configuration showed the most consistent performance.

The analysis of Table 1 indicates that the synthesized studies operate across two main analytical layers. The first layer concerns the development of rainfall thresholds themselves, whether through national threshold revision, dynamic threshold modelling, or intensity–duration threshold formulation. The second layer focuses on evaluating the quality of satellite-based rainfall data, reinforcing the idea that a threshold can only be as reliable as the rainfall input on which it is built. With the emergence of the Bali/Badung cluster, Indonesian literature appears to be moving beyond national system updates and Java-focused studies toward the development of regional laboratories for more detailed methodological experimentation (Figure 2). Figure 2 highlights the concentration of studies in Java and Bali. This indicates that the national evidence base is still shaped by a relatively narrow set of study regions; therefore, any generalization of rainfall thresholds to the national scale should be made with caution.

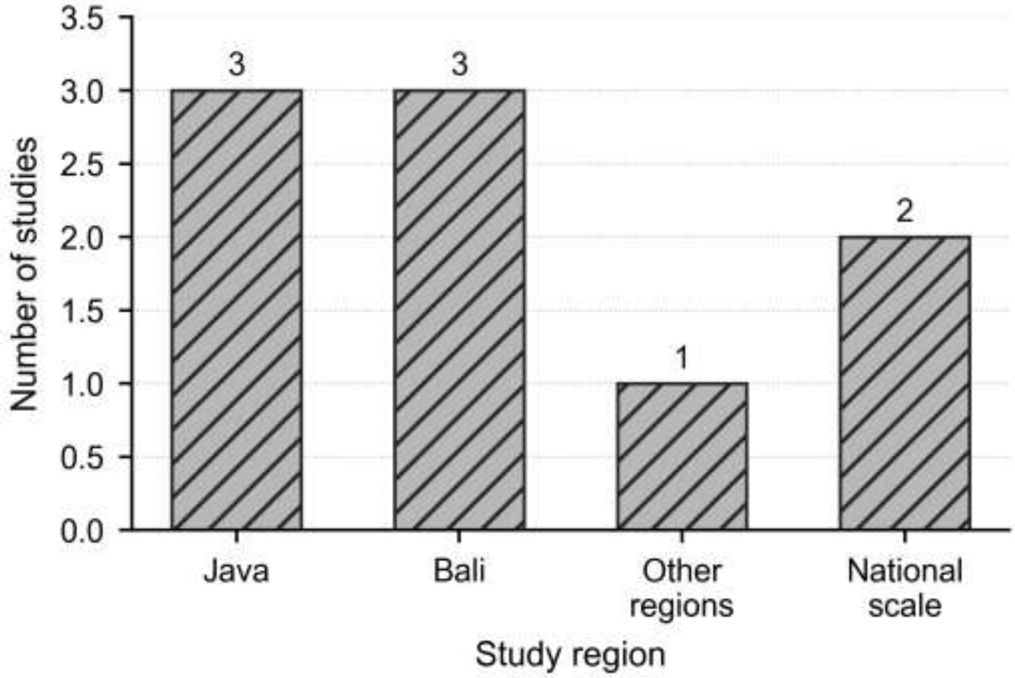

Figure 2. Regional distribution of reviewed studies on satellite-based rainfall thresholds for landslide initiation in Indonesia.

The synthesis reveals a clear shift in the satellite precipitation products used across the reviewed studies. Early research relied primarily on TRMM, whereas more recent studies have increasingly adopted GPM/IMERG, GSMaP, CMORPH, and PERSIANN. The Indonesian literature does not yet identify a single product that consistently outperforms the others. Instead, it emphasizes that product performance is highly context-dependent, varying according to study location, temporal scale, and the application of bias correction or data-fusion procedures.

4.2 Typology of Threshold Methods

Four major methodological typologies were identified (Figure 3): (1) empirical intensity–duration thresholds; (2) thresholds based on effective antecedent rainfall; (3) dynamic and probabilistic thresholds; and (4) cumulative thresholds supported by data integration or fusion procedures. This finding indicates a clear shift from fixed-threshold models toward approaches that are more context-sensitive, data-aware, and decision-oriented.

Figure 3 illustrates the methodological transition from TRMM-based empirical I–D thresholds to dynamic thresholds, data integration, fusion-based approaches, and hourly bias-corrected thresholds. This evolution suggests that methodological progress in this field is not driven solely by the replacement of one satellite product with another, but more fundamentally by the growing ability to define rainfall events more precisely and to manage uncertainty in satellite-derived rainfall data.

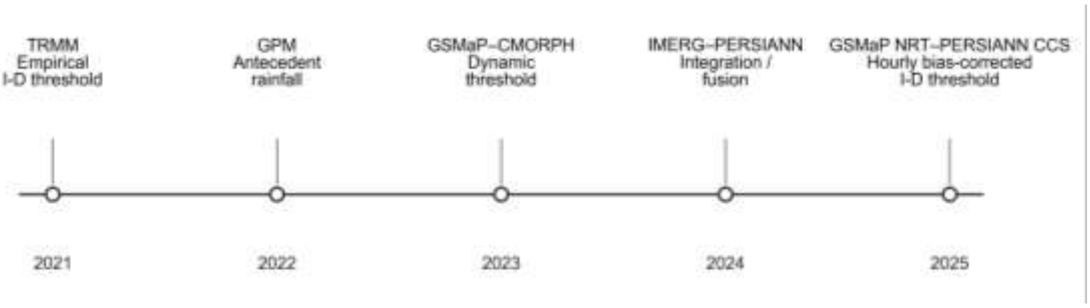

Figure 3. Evolution of satellite-based rainfall threshold approaches for landslide initiation in Indonesia, 2021–2025.

4.3 Threshold Performance

ROC and AUC emerged as the most frequently used validation metrics across the reviewed studies. In the Progo Catchment, the threshold developed using GSMaP-GNRT produced performance that was comparable to, and slightly better than, the rain-gauge-based threshold, whereas the CMORPH-based threshold showed lower performance. In Badung, the best performance was achieved when IMERG and PERSIANN were integrated, with the highest AUC value of 0.903 obtained for the 30-day cumulative rainfall threshold. The Metro Catchment study further highlights the importance of bias correction and temporal-window configuration in improving threshold consistency (Table 2). Overall, Table 2 indicates that the strongest threshold performance generally occurs when satellite rainfall data are not used in their raw form, but are corrected, calibrated, or integrated with other datasets.

Table 2. Summary of Threshold Performance in Indonesian Studies

Study	Main Performance Indicator	Performance Finding
(Muntohar et al., 2021)	ROC and seven statistical indices	The model showed acceptable accuracy, although the error remained relatively high.
(Yuniawan et al., 2022)	ROC / ILEWS accuracy evaluation	The revised threshold performed better than the single national threshold.
(Satyaningsih et al., 2023)	AUC	The rain-gauge-based threshold achieved an AUC of 0.72, GSMaP-GNRT achieved 0.73, and CMORPH-CRT achieved 0.64.
(Aryastana, Dewi, & Wahyuni, 2024a)	AUC	PERSIANN achieved an AUC of 0.755, IMERG achieved 0.769, and the integrated IMERG–PERSIANN dataset achieved the highest AUC of 0.903.
(Aryastana, Dewi, & Wahyuni, 2024b)	AUC	The 15-day cumulative rainfall threshold produced an AUC above 0.75.
(Aryastana, Dewi, Wahyuni, et al., 2024)	AUC	The second-fusion dataset achieved an AUC of 0.82 for the 15-day cumulative rainfall threshold.
(Aina et al., 2025)	I–D threshold consistency	GSMaP NRT outperformed PERSIANN CCS, while the 24-h no-rain gap configuration produced the most consistent threshold.

4.4 Emerging Gaps

Four major gaps consistently emerged from the synthesis (Table 3). First, there is a spatial gap, as the existing studies remain concentrated in Java and Bali. Second, a methodological gap is evident because definitions of rainfall events, antecedent rainfall windows, and threshold formulations are not yet standardized. Third, a data-related gap persists, as no single satellite precipitation product performs best across all contexts. Fourth, an operational gap remains because not all studies evaluate threshold performance within the practical decision-making logic of daily warning operations. Table 3 indicates that the research gap in Indonesia is not only a matter of the limited number of studies, but also reflects inconsistencies in research design across the existing literature.

Table 3. Research Gaps Emerging from the Synthesis

Type of Gap	Manifestation in the Corpus	Implication
Spatial	The corpus remains concentrated in Java and Bali.	Rainfall thresholds cannot yet be directly generalized to the whole of Indonesia.
Methodological	Definitions of rainfall events, antecedent windows, and threshold forms vary across studies.	Cross-study comparison becomes difficult and may be vulnerable to interpretive bias.

Data-related	Different satellite products show varying performance depending on location and temporal scale.	Bias correction, data fusion, and local validation are essential prerequisites.
Operational	Not all studies assess false alarms and missed events.	The readiness of thresholds for daily warning operations requires further testing.

5 Discussion

The review indicates that research on satellite-based rainfall thresholds for landslide initiation in Indonesia should not yet be understood as a fully established body of evidence. Rather, it represents a field in transition, moving from an initial proof-of-concept phase toward a stage of methodological optimization. Research in Indonesia is no longer limited to asking whether satellite rainfall data can be used to develop landslide thresholds. It has advanced toward more refined questions concerning the most suitable satellite products, the definition of rainfall events, bias correction procedures, and the translation of thresholds into operational decision-making within landslide early warning systems (LEWS).

The first major finding is that Indonesia is gradually moving away from the logic of a single national threshold. The revision of ILEWS and the development of dynamic thresholds demonstrate that rainfall thresholds in Indonesia are more appropriately understood as the outcome of interactions among rainfall characteristics, slope conditions, and diverse spatial contexts. In other words, thresholds are context-sensitive rather than one-size-fits-all (Satyaningsih et al., 2023; Yuniawan et al., 2022).

The second finding is that satellite precipitation products do not perform consistently across all contexts. The studies reporting the strongest results are those that treat bias, resolution, and data integration as central methodological concerns. This implies that satellite rainfall products should not be used as direct, unprocessed substitutes for rain-gauge observations. Instead, they should be validated, bias-corrected, calibrated, or fused with other datasets before being applied in threshold development (Aina et al., 2025; Aryastana, Dewi, & Wahyuni, 2024a).

The third finding is the growing importance of antecedent rainfall and hydrological preconditioning in Indonesian threshold studies. This suggests that the rainfall–landslide relationship cannot be adequately explained by rainfall during the triggering event alone, but must also be interpreted in relation to the prior hydrological state of the slope. Consequently, future threshold models should be more sensitive to rainfall-event structure and to the water-storage conditions within slopes (Abancó et al., 2024; Nocentini et al., 2024).

From a practical perspective, the future of LEWS in Indonesia is unlikely to depend on a single uniform national rule. Instead, it will more likely require a layered and tiered system. A national framework remains necessary, but its threshold rules should be sufficiently flexible to be adapted to regional scales, catchment-level contexts, or specific territorial classes. This direction requires the integration of rainfall thresholds with evaluations of false alarms and missed events, rather than relying solely on the reporting of AUC values.

6 Conclusion

Based on the findings of this systematic literature review, it can be concluded that research on satellite-based rainfall thresholds for landslide initiation in Indonesia has evolved from relatively general early approaches toward more localized, dynamic, and validation-oriented frameworks. The reviewed literature indicates that the use of a single national threshold is insufficient for Indonesia’s highly diverse environmental context. As a result, recent studies have moved toward region-specific threshold revisions based on landslide events, the use of dynamic rainfall-event approaches, and the evaluation of multiple satellite precipitation products, including GPM/IMERG, GSMaP, CMORPH, and PERSIANN.

The most important insight emerging from this review is that the reliability of satellite-based thresholds in Indonesia is not determined primarily by identifying one universally superior satellite product. Rather, it depends on the degree of fit among the satellite product, temporal scale, rainfall-event definition, and the strategy used for bias correction or data integration. In practical terms, the findings suggest that the future development of landslide early warning systems (LEWS) in Indonesia should be directed toward a multi-level architecture, supported by bias correction and data integration, and evaluated using operational performance measures such as false alarms and missed events.

This study has several limitations, including the relatively small size of the review corpus, the dominance of studies from Java and Bali, and methodological heterogeneity across the included studies. Therefore, future research should expand beyond the currently dominant research regions, standardize landslide-event inventories, integrate satellite precipitation products with weather forecasts and field observations, and evaluate threshold performance across regions using operationally relevant metrics.

Declaration of Competing Interests
The authors affirm that they do not have any known competing financial interests or interpersonal conflicts that might have appeared to have an impact on the research presented in this paper.

Funding
This research was supported by the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia under Main Contract No. 287/C3/DT.05.00/PL-BARU/2026 and Derivative Contract Nos. 691/DST/LL8/DT.05.00/2026 and 698/UNWAR/DPPM/PD-13/2026.

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