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LITERATURE REVIEW Open Access

Puting beliung: Understanding Indonesia's small-scale tornadoes and the path forward—A literature review

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Abstract

Puting beliung (PB), a tornado-like event in Indonesia, poses significant threats to communities and infrastructure, yet research on their characteristics and impacts remains limited. This study systematically reviews the progress of PB research in Indonesia through an analysis of 58 relevant studies, focusing on geographical distribution, characteristics, impacts, and mitigation efforts. Using Google Scholar as the primary search engine for scientific journal retrieval and implementing the PRISMA methodology for systematic literature review, this study ensures a comprehensive and structured analysis of existing research. Findings indicate that PB events predominantly occur in Java, with notably fewer documented cases in eastern Indonesia. These events are influenced by atmospheric conditions and spatiotemporal patterns, with psychological and structural impacts on affected communities. Existing mitigation strategies, including early warning systems, show promise but face challenges in public engagement and coordination, particularly in post-disaster recovery phases. The review highlights the need for integrating advanced technologies such as remote sensing and machine learning to improve prediction accuracy and develop a comprehensive PB event database. By synthesizing existing research, this study identifies and underscores the necessity for more extensive investigations, particularly under-research regions. Future research should prioritize improving forecasting models, expanding the geographical scope of studies, and enhancing disaster management strategies to minimize PB-related risks. Strengthening public awareness and response mechanisms is crucial to reducing vulnerabilities and improving resilience.

Keywords: puting beliung; extreme weather; systematic review; PRISMA; Indonesia.

Introduction

Indonesia's geographical setting as a tropical archipelago makes it particularly vulnerable to extreme weather events, defined as weather conditions that deviate significantly above or below normal parameters, resulting in destructive and detrimental impacts (Lestarianto et al., 2023). Among the prevalent extreme weather phenomena in Indonesia is puting beliung (PB), which, according to the National Disaster Management Agency (BNPB), rank as the second most frequent highest hydrometeorological disaster in Indonesia over the past five years (BNPB, 2024). PB is defined as rotating strong winds that emerge from Cumulonimbus (Cb) clouds, with velocities exceeding 34.8 knots or 64.4 km/hour, occurring over brief periods (BMKG, 2010). This extreme phenomenon has exhibited an increasing trend in recent years (Ali & Hidayati, 2016) and has been reported to occur across virtually all regions of Indonesia (Darman, 2019).

PB is a local wind phenomenon in Indonesia frequently characterized as a small-scale or weak tornado (Mujiasih et al., 2014; Silitonga et al., 2017), strong wind, or storm wind (Nurjani et al., 2013). The local wind is defined as a local-scale wind phenomenon that occurs in an area of a few centimeters to one kilometer or more and lasts for fewer than 24 hours (Windy, 2024). Besides PB, there are several other local wind phenomena in Indonesia, such

as the Gending wind in East Java, Bahorok wind in North Sumatra, Barubu wind in South Sulawesi, Kumbang wind in West Java, Wambrau wind in Papua, and others (Fariduzzaman, 2010). Generally, PB occurs in relatively confined areas and for brief durations (Aliftha et al., 2020); therefore, detecting, predicting, and analyzing this phenomenon is quite challenging, particularly in obtaining data with appropriate spatial and temporal resolution.

The impact of PB in Indonesia is significant despite their brief duration. PB in Indonesia generally lasts between 5-10 minutes, unlike tornadoes in the United States, which can last up to 1 hour. This is because PB in Indonesia is generally generated from Cb clouds produced by the convection process (Siswanto, S., Supari, 2012), while strong tornadoes in the United States are primarily generated from more extensive and complex supercell clouds that formed in frontal areas (Kobayashi et al., 2007; Romanskii et al., 2018; Wang & Min, 2023). Recent PB events highlight their destructive potential – in February 2024, a single PB incident in Rancaekek, Bandung, West Java, damaged 534 buildings and injured 33 people (Saputra, 2024). The economic toll is substantial, with documented losses reaching IDR 280.835 billion in Java alone during 1990-2011 (Nurjani et al., 2013). Beyond physical and economic damage, PB events also inflict psychological trauma, particularly among vulnerable populations such as children (Nikmah & Hazim, 2023).

Previous research has investigated different elements of PB in Indonesia, such as their spatial-temporal distribution, impacts, climatic characteristics, and formation mechanisms. However, this research has primarily been localized and scattered, with no overall national viewpoint. The systematic literature review synthesizes and analyzes research advancements on PB in Indonesia over the past decade. The analysis highlights several major research topics and advances, including research distribution and focus, methodological approaches, notable discoveries, research gaps, and future research objectives. This study covers the present level of PB research in Indonesia and highlights crucial areas that require additional exploration.

This study aims to analyze the development of PB research in Indonesia using a systematic literature review, focusing on major elements such as geographical distribution, features, impacts, and mitigation efforts. The review will contribute to a complete overview of public health research in Indonesia by synthesizing existing knowledge, finding gaps, and suggesting future research objectives for enhanced prediction and mitigation.

Methods

Key research questions

The primary research question of this study is to examine the development of PB research in Indonesia, which is explored through several key sub-questions. First, the study investigates the temporal trends in PB research to understand how scholarly interest has evolved. It also examines the most commonly employed research methodologies to identify prevailing analytical approaches. Additionally, the study assesses the geographical distribution of research efforts, highlighting which regions in Indonesia have received the most scholarly attention. Furthermore, it explores the characteristic features of PB in the Indonesian context, including their causative factors and triggering conditions. Beyond meteorological aspects, the study also evaluates PB events' social, economic, and environmental impacts. It further reviews mitigation and adaptation strategies or investigates to reduce PB risks. Lastly, the study examines the extent to which PB monitoring and prediction technologies have been developed and implemented in Indonesia, providing insight into current capabilities and future directions for improving early warning systems.

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)

The PRISMA reporting guidelines are intended to assist authors disclose clearly why their systematic review was carried out, what methodologies they employed, and what they discovered. The PRISMA reporting guidelines, also known as PRISMA 2020, provide recommendations for reporting systematic studies that assess the impact of interventions. PRISMA 2020 is supplemented by extensions that provide guidelines for reporting specific types

or components of systematic reviews and other forms of evidence synthesis (PRISMA, 2024). This study employs the PRISMA 2020 Flow Diagram (*PRISMA Flow Diagram*, 2024), which represents the data flow across the various stages of a systematic review. It depicts the number of records identified, included, and excluded, as well as the reasons for exclusions.

Literature search strategy

The literature search was conducted using the PRISMA methodology, which was limited to a systematic review only. The following constraints were applied in conducting the literature search:

1. Google Scholar was utilized as the primary database search engine. This search engine was utilized to retrieve all BP-related literature in Indonesian and English that was unavailable in other academic databases such as Scopus, Web of Science, and similar platforms.
2. The literature period was restricted to publications from 2010 to 2024. This selection of periods is considered sufficient to provide an overview of the development of disaster management research in the past decade;
3. Publications in national journals and proceedings were included regardless of SINTA indexing status;
4. Undergraduate theses, master's theses, doctoral dissertations, and technical reports were excluded from the literature. This is done because these documents have generally not gone through the peer review process and external validation from experts in their fields, as in scientific journals. Ease of access is also a consideration, as some institutional repositories restrict access to these documents;
5. Publications in English and Indonesian languages were considered. This aims to gain perspectives from local Indonesian research that may not be published in English;
6. PDF file availability was required.

This systematic literature review focused on the analysis, prediction, and simulation of PB in Indonesia. Studies on PB outside this scope were excluded. The literature collection was conducted using the following keywords: ("puting beliung" OR "small-tornado" OR "funnel cloud" OR "tornado" OR "whirl wind" OR "landspout" OR "wind vorticity" OR "angin ribut" OR "extreme wind" OR "angin ekstrim" OR "angin ekstrem") AND ("indonesia" OR "java" OR "kalimantan" OR "sulawesi" OR "sumatra" OR "bali" OR "nusa tenggara" OR "maluku" OR "papua").
The literature obtained based on the above keywords underwent a two-stage screening process: first, based on the relevance of titles and abstracts, and second, based on the complete content of the publications. The results of these two screening stages were then synthesized and analyzed to address the research questions and achieve the objectives of the systematic literature review.

Data extraction strategy

The review, synthesis, and analysis process were conducted to extract data from selected literature to obtain an overview of PB research development in Indonesia. The extracted data comprises the following:

1. Bibliographic information: consisting of literature title, authors, journal name, and publication year;
2. Research methodology: research type (quantitative, qualitative, mixed-method), research data, data collection techniques, and analytical tools employed;
3. Research location: studied regions or areas, geographical characteristics of the locations;
4. PB characteristics: patterns or distinctive features of PB such as morphology, intensity, spatiotemporal distribution, etc.;
5. Key findings: causal factors of PB, identified PB characteristics, resulting impacts (social, economic, environmental), proposed mitigation and adaptation strategies;
6. Technology utilized: monitoring methods, analytical methods, prediction, and early warning systems;
7. Research gaps: research limitations acknowledged by authors and recommendations for future research.

Results and Discussions

Literature review selection procedures

The literature search and selection procedures in the systematic literature review concerning PB in Indonesia are presented in Fig. 1. During the literature search phase in the Google Scholar database, by applying the procedure as described in the previous literature search strategy section, 783 publications were obtained. In the first screening phase, the total number of publications was reduced to 114 based on the relevance of titles and abstracts. Furthermore, the second screening stage was carried out through full-text screening, which resulted in 66 publications. Further checks were conducted to eliminate duplicate publications, publications without complete PDF files, and publications before 2010. The final result from these three screening phases produced 58 publications.

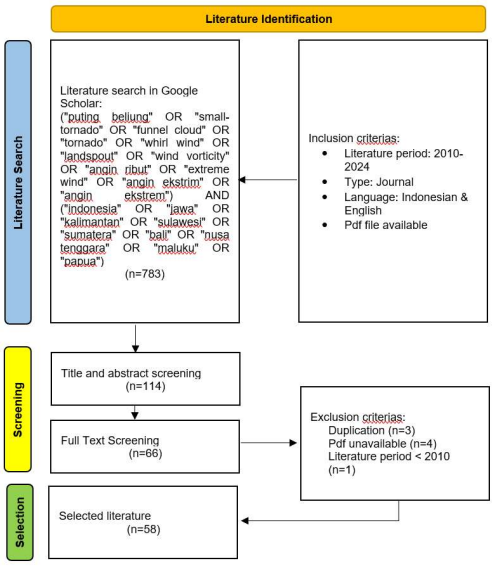

Figure 1. Literature search flow.

Keyword Co-occurrence Analysis of PB Research Using VOSviewer

Using bibliographic information from 58 selected references using the VOSviewer application (Leiden University, 2023), a bibliometric analysis was conducted using research keywords to examine the scope and trends of PB research in Indonesia over time, as presented in Figure 2.

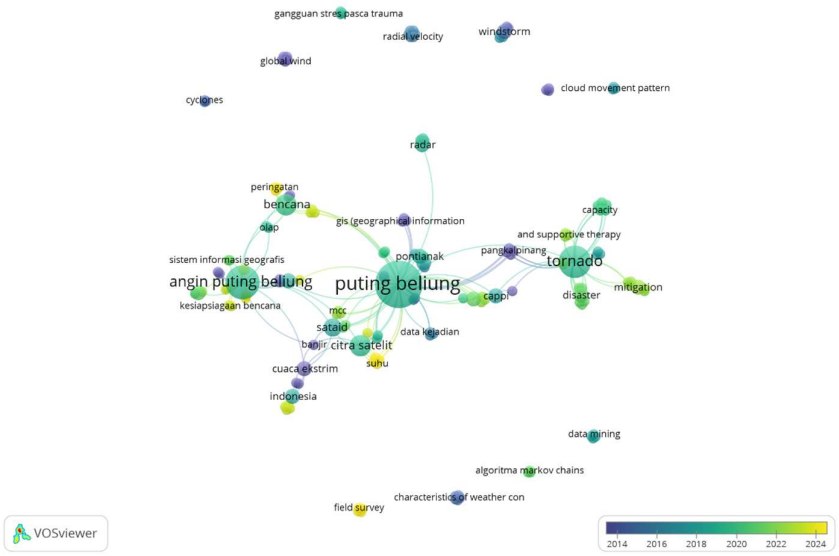

Figure 2. Keywords overlay visualization of PB research in Indonesia based on selected literature.

Based on the bibliometric analysis of 58 selected literature sources, there are 166 keywords indicating three primary keywords in tornado research: "puting beliung", "angin puting beliung", and "tornado." The keyword variations demonstrate the implementation of multidisciplinary approaches in studying PB in Indonesia, including geography, statistics, information technology, disaster management, and psychology. Temporal trend analysis reveals that during the initial period (2010-2016, blue cluster), research predominantly focused on essential meteorological aspects such as extreme weather, global wind, cyclones, and cloud movement patterns. Additionally, preliminary studies on Post-Traumatic Stress Disorder (PTSD) were conducted to analyze the psychological impacts of this phenomenon.

Research extensively utilized remote sensing technologies such as weather radar and satellites in the middle period (2017-2020, green cluster). Focus on the terms puting beliung and tornado as primary topics has become increasingly prominent. The development of early warning systems commenced, as evidenced by the emergence of the keyword "disaster warning."

In the recent period (2021-2024, yellow cluster), there has been a significant increase in the utilization of information technology and data analysis, as indicated by keywords such as "data mining" and "Markov chains algorithm." Greater emphasis on disaster management and applying geographic information systems and PB incident data analysis have become more prevalent. Enhanced attention to social aspects and post-disaster recovery is also apparent, exemplified by keywords such as "capacity" and "supportive therapy." Several keywords that appear disconnected from the main PB theme, such as "field survey" and "data mining," indicate that these methods or approaches represent relatively new or less integrated research areas within the comprehensive study of PB.

Analysis of Research Methods in Selected PB Studies

Most PB research in Indonesia utilizes the case study method, accounting for 28 sources (48%). This is followed by machine learning methods with 10 sources (17%), qualitative methods with 9 sources (16%), statistical methods with 7 sources (12%), and geospatial methods with 4 sources (7%). Aside from PB occurrence data, the

most commonly used data types in PB research include satellite data, surface synoptic data, reanalysis data, topographic data, primary survey/interview data, weather radar data, and others, as presented in Fig. 3.

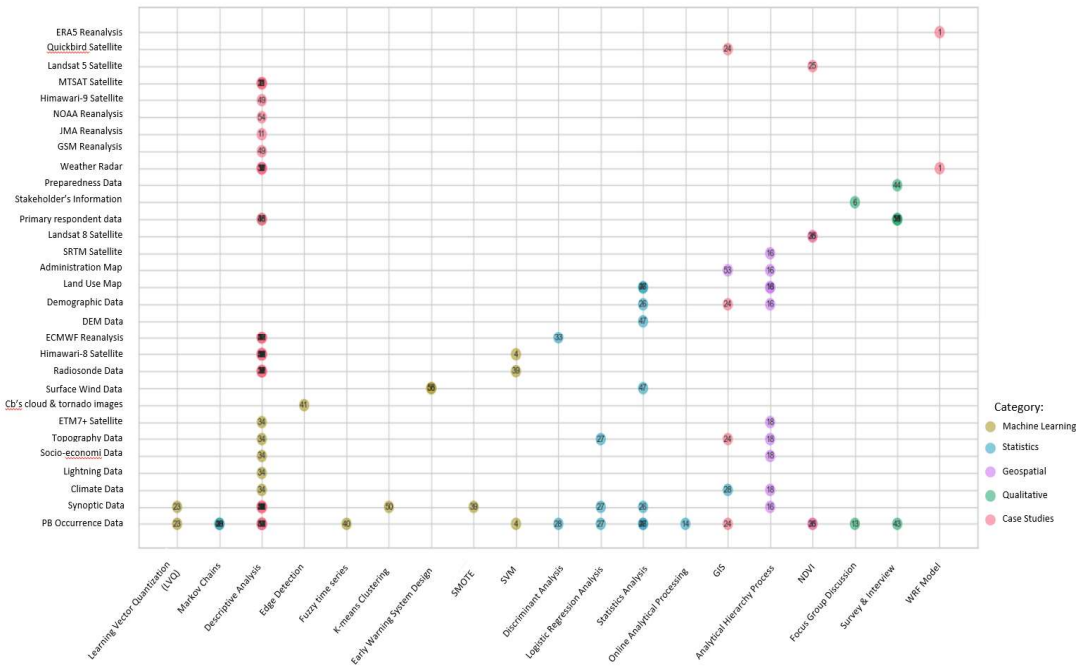

Figure 3. Data and research methods on PB in Indonesia based on selected literature.

The tools utilized in the selected 58 studies include:

1. Remote sensing technology
   - Doppler C-band Weather Radar (CDR) for detecting cloud characteristics and wind patterns (Handayani, D., Samapta, B.T, Utami, P.N., Fuadah, L.M., Margiono, 2019; Rindrasih & Mujiasih, 2015).
   - Himawari-8/9 Satellite Imagery for analyzing cloud-top temperature and convective cloud growth (Agung & Darmawan, 2024; Prasetyo et al., 2020).
   - MTSAT Satellite Imagery for cloud cover analysis (Silitonga et al., 2017).
   - Landsat Imagery for vegetation and land use analysis (Ruslana, Z.N., Sulistiyowati, 2020).
2. Geographic Information Systems (GIS)
   - ArcGIS for event mapping and spatial analysis (Fadillah & Nurdin, 2021).
   - WebGIS for information visualization and dissemination (Ramadhani et al., 2022).
3. Numerical modeling
   - WRF (Weather Research and Forecasting) Model for simulating atmospheric conditions (Yulihastin, 2023).
   - ERA5 ECMWF Reanalysis Data for meteorological parameter analysis (Prasetyo et al., 2020).
4. Early warning systems
   - Arduino Uno is a microcontroller for detection systems and an SMS Gateway for warning information dissemination (Murdyaningrum et al., 2016).

- Wind speed, wind direction, and temperature sensor (Saputro et al., 2024).

5. Machine learning
   - K-Means Algorithm for clustering vulnerable areas (Ramadhan & Utara, 2024).
   - Support Vector Machine (SVM) for event classification, and SMOTE Algorithm for handling imbalanced data (Novitasari et al., 2020).
   - Markov Chain for event prediction (Dalimunthe et al., 2023; Hidayati et al., 2021).
6. Analytical software
   - SATAID for satellite imagery interpretation (Agung & Darmawan, 2024).
   - GrADS for meteorological data visualization and analysis (Lumbangaol & Munandar, 2018).
   - RAOB for radiosonde data analysis (Yudistira et al., 2019).
7. In-situ observation technology
   - Automatic Weather Station (AWS) for surface weather parameter measurement (Anam & Amri, 2021).
   - Radiosonde for vertical atmospheric profiling (Fernanda et al., 2024).
8. Image processing
   - Edge detection techniques for analyzing chaotic phenomena in cumulonimbus clouds (Wanayumini et al., 2018).

Geospatial distribution of PB study locations in Indonesia

The focus of PB research locations over the past 14 years has generally been in the western and central parts of Indonesia. The three provinces with the most PB research are Central Java (12 studies), West Java (7 studies), and East Java (7 studies). Research with a national (Indonesia) focus includes 8 studies, while 1 study focuses on Java. There are still gaps in research locations, especially in eastern Indonesia, as well as several provinces in Sumatra, Kalimantan, and West Nusa Tenggara. Thus, it is necessary to conduct PB research in these locations, considering that disasters occur in almost all parts of Indonesia (Lee et al., 2017). Further details of the geographical distribution of PB research locations are presented in Fig. 4.

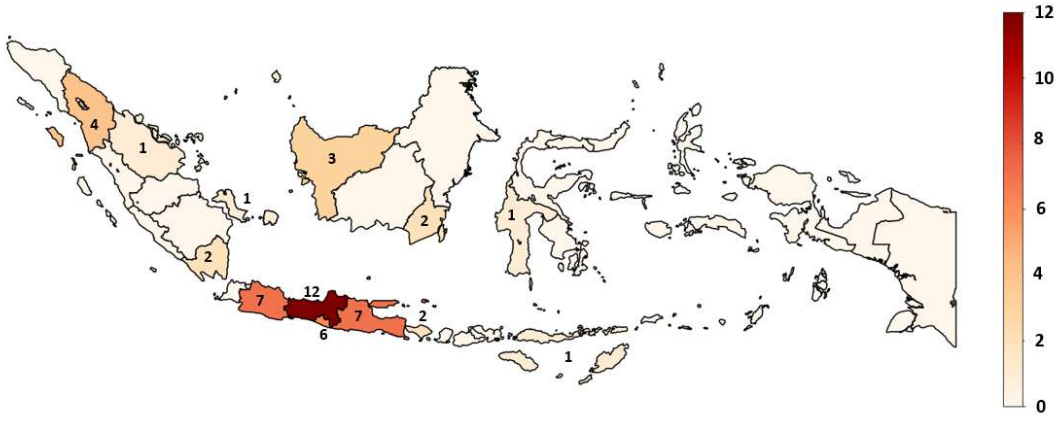

Figure 4. The distribution of selected literature study location; the legend presents the number of PB studies in each province in Indonesia.

Analysis results and key findings of PB research

The consolidated summary of results and main findings, extracted from a systematic analysis of 58 selected studies on PB in Indonesia, is comprehensively presented in Table 1, providing a detailed overview of the distribution, characteristics, mechanisms, impacts, and meteorological aspects of mitigation efforts.

Table 1 Results and key findings reported by selected literature

No.	PB Aspect	Results & Key Findings
1	Physical Characteristics	PB is defined as a funnel or spiral formed by a Cb cloud that touches the ground, rotates at a speed ranging from 20 to 64 knots, and lasts shorter than 10 minutes. The trajectory is a straight line fewer than ten kilometers long. This understanding can help guide early warning systems and preparedness efforts. However, variation in characteristics (for example, wind speed and duration) indicates that a one-size-fits-all strategy for mitigation may be ineffective. Future studies could concentrate on building tailored approaches depending on the peculiarities of individual PBs in different areas.
2	Spatiotemporal Patterns	The concentration of PB occurrences on Java Island, particularly in March and October, emphasizes the importance of seasonal planning. Understanding when PBs are most likely to occur (midday to afternoon) will help improve community awareness and response plans.
3	Development Mechanisms	The findings highlight vertical vorticity anomalies, wind shear, and updraft dynamics as important drivers in PB formation. Furthermore, local topographical and meteorological variables, such as surface heating and land usage, have an impact. This knowledge improves modeling efforts to forecast PB occurrences by combining large-scale and localized atmospheric data.
4	Impacts	PB causes fatalities, economic losses, and psychological suffering, with Central Java experiencing the highest damage rates. The discovery of PTSD-related anxiety in impacted populations emphasizes the importance of psychological treatments alongside physical disaster relief. The data also imply moderate community resilience, demanding improved preparedness efforts.
5	Synoptic Weather Conditions	The observed pre-event meteorological changes (temperature drop, pressure fall, increased humidity, and wind speed) may be PB predicting indicators. However, disparities in climatic conditions 12 hours before an occurrence indicate that real-time monitoring is vital rather than depending on larger climatological trends.
6	Signatures on Remote Sensing Observation Data	The identification of Hook echo patterns, high reflectivity values (>40 dBZ), and wind rotation at low levels (0.5-1 km) strengthens radar-based PB detection. However, the brief duration of PB makes it challenging to provide real-time warnings. Cloud top temperature (≤-60°C) and certain Cb cloud forms (single-cell, supercell) are additional remote sensing markers for early warning systems.
7	Atmospheric Instability	PB occurs in moderate to severely unstable conditions and has high CAPE, LI, and BRN values, implying that atmospheric instability indicators can be used in prediction models. However, weak SWEAT values show that PB formation mechanisms differ from regular tornadoes, necessitating specialist forecasting factors.
8	Topography's Role	The findings confirm that low vegetation density, high surface temperatures, and changes in land cover all contribute to PB risk. This highlights the importance of urban heat islands and deforestation in aggravating PB

		occurrences. Future mitigation should involve urban design techniques, such as greater greenery and improved land-use regulations.
9	Simulation & Prediction	The findings highlight several prediction methodologies, including WRF modeling for storm structure simulation, Markov Chains for PB likelihood estimation, SVM and SMOTE for wind classification, and GIS-based risk mapping.
10	Mitigation & Adaptation Strategies	The findings highlight structural (land-use planning, PB-resistant structures, early warning systems) and non-structural (education, psychological support, community engagement) mitigation initiatives. Key challenges include limited stakeholder coordination, poor public disaster awareness, and short public warning times (14 minutes on average). SMS-based alerts, psychological therapies, and readiness training for vulnerable populations (senior citizens, children, and people with disabilities) are all promising options. However, mitigation measures remain fragmented, necessitating stronger institutional frameworks and cross-sector collaboration.

Knowledge gaps in PB research

The development of PB research in Indonesia over approximately the past 14 years shows a trend of increasing complexity, both quantitatively and qualitatively. This is evident from the more sophisticated data and methods to analyze this extreme phenomenon. The findings from these studies provide valuable insights into scientific understanding, detection methods, analysis, and even prediction of PB in Indonesia. However, there remains a gap, particularly regarding the spatial coverage of PB research, especially in Indonesia's central and eastern regions. Predictive studies on PB are also relatively limited compared to case study analyses.

Advanced technologies such as remote sensing have significantly contributed to PB research, as evidenced by the extensive use of weather satellite data in many selected references. There is still considerable potential for further development in PB research by maximizing weather radar data and other observational data, such as upper-air observations, lightning data, and geospatial data. Likewise, numerical weather models and machine learning still offer ample opportunities for research on this phenomenon to improve understanding, prediction, and mitigation.

Another important note that warrants attention is a verified and digitized database of PB events. Historical data is crucial for research, disaster mitigation, policy-making, infrastructure planning, public awareness, and potential international collaboration, particularly in research and tornado disaster management.

Future research directions and recommendations

Based on the analysis of existing literature on PB in Indonesia, future research on this extreme phenomenon is likely to focus on improving prediction accuracy and gaining a deeper understanding of its physical and dynamic processes. Artificial intelligence technology and the integration of observational data from various sources could be employed to develop more accurate detection and prediction models.

Further development in PB research could also be directed toward a more comprehensive analysis of cloud microphysical processes, studies on the impact of climate change on PB activity, and investigations into the socio-economic impacts of this phenomenon through interdisciplinary studies. Additionally, examining environmental impacts and land use in PB formation, as well as developing a comprehensive digital database of PB events that includes intensity information, are important pursuits.

These future research directions aim to enhance scientific understanding, improve detection and prediction capabilities, and ultimately contribute to strengthening early warning systems that will increase public safety against the potentially destructive impacts of PB.

Conclusions

The systematic literature review on "puting beliung" events in Indonesia reveals a concerning trend of increasing frequency and destructive impacts associated with these small-scale tornado phenomena. The analysis of 58 relevant studies highlights significant gaps in knowledge, particularly regarding the geographical distribution and characteristics of PB events. Key findings indicate that PBs predominantly occur in Java, with specific spatiotemporal patterns and trigger mechanisms influenced by atmospheric conditions. The research underscores the necessity for an enhanced understanding of the physical processes underlying PB occurrences, and the psychological and structural impacts on affected communities.

Furthermore, the review emphasizes integrating advanced technologies, such as remote sensing and machine learning, into future research endeavors. While existing mitigation strategies, including early warning systems and community outreach, have shown promise, challenges remain in effective coordination and public engagement. The study advocates for a comprehensive approach to disaster management that incorporates social aspects and post-disaster recovery, particularly in under-researched regions of eastern Indonesia and parts of Sumatra and Kalimantan. Future research should prioritize improving prediction accuracy and developing a robust database of PB events to better inform disaster preparedness and response efforts.

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