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Mapping CBRNE Preparedness Gaps in Indonesia: Integrating Public Health, Technology, Governance, and GIS

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ABSTRACT: CBRNE threats pose complex risks to public health systems, particularly in countries with diverse geographical and institutional settings such as Indonesia. This study examines the readiness of Indonesia's public health system to address CBRNE threats and identifies strategies for strengthening preparedness through an integrated approach. A qualitative descriptive design was applied, using data from in-depth interviews with experts, field observations, regulatory analysis, and secondary sources. Data were analyzed using NVivo with a thematic approach. The findings reveal that preparedness remains limited and is characterized by fragmented governance, disparities in healthcare capacity, insufficient technological infrastructure, lack of standardized operational procedures, and weak risk communication. These constraints reduce the system's ability to respond effectively to complex and high-impact threats. The study proposes an integrated framework that connects health system capacity, technological and engineering support, and collaborative governance to enhance national preparedness. Strengthening efforts should focus on improving healthcare infrastructure and workforce competencies, while advancing early detection systems, laboratory integration, and interoperable health information systems. This study contributes to the development of a more resilient and adaptive public health system by bridging health sciences, engineering, and policy in addressing CBRNE challenges

1. INTRODUCTION

The evolving dynamics of global threats indicate that public health is no longer limited to the control of infectious diseases but also encompasses preparedness for high-impact hazards such as Chemical, Biological, Radiological, Nuclear, and Explosives (CBRNE) [1]. These threats are inherently complex, with the potential to cause mass casualties, long-term health consequences, and disruptions to social and environmental stability. Advances in technology, increased global mobility, and the growing risk of conflict and industrial accidents further heighten the likelihood of both intentional and unintentional CBRNE incidents. This calls for an approach that goes beyond traditional health perspectives and incorporates technological, environmental, and governance dimensions [2].

From a public health perspective, CBRNE threats require a health system that is capable of early detection, rapid response, and effective recovery. The role of the health system has expanded beyond curative services to include surveillance, risk management, crisis communication, and cross-sector coordination. This aligns with the concept of health system resilience, which emphasizes the capacity of systems to absorb shocks, adapt to change, and transform in response to complex emergencies [3]. As an archipelagic country with diverse geographical and demographic characteristics and high disaster vulnerability, Indonesia faces distinct challenges in addressing CBRNE threats. In addition to natural hazards and industrial accidents, the country is also exposed to non-conventional risks that can directly affect public health [4]. Although various policies have been developed to strengthen health systems and disaster management, their implementation remains constrained by limited interoperability across institutions, gaps in technological capacity, uneven distribution of health resources, and insufficient integration between civilian and military components in crisis response [5].

Previous studies have largely approached CBRNE from defense, security, or emergency management perspectives, often focusing on technical and operational aspects. In contrast, research that integrates CBRNE risk management into public health systems remains limited, particularly in developing country contexts such as Indonesia [6]. Existing approaches also tend to be fragmented across technological, policy, and institutional dimensions, making it difficult to capture system-wide preparedness [7]. This highlights the need for a more integrative and interdisciplinary approach that connects health, technology, and governance within a unified analytical framework [8]. In line with the scope of Science, Engineering and Health Studies, which emphasizes the integration of health sciences, engineering, and applied science, this study examines the readiness of Indonesia's public health system to respond to CBRNE threats using a comprehensive approach. The study not only identifies key challenges but also proposes strategic responses based on system integration, technological utilization, and evidence-based policy development [9].

This study contributes by developing an integrated health, technology, and governance framework that advances existing approaches to CBRNE preparedness, particularly in developing country contexts. Unlike prior studies that often examine CBRNE from fragmented perspectives such as public health, security, or technology this research brings these dimensions together into a unified analytical model [10]. The framework links health system capacity, including workforce readiness and service delivery; technological components such as early warning systems, laboratory networks, and interoperable data systems; and governance mechanisms, including policy integration and cross-sector coordination [11]. Empirically grounded in qualitative data and NVivo-based analysis, the study provides both analytical depth and contextual relevance. Conceptually, it extends the notion of health system resilience by embedding technological and governance dimensions within a single structure. Practically, it offers a foundation for more adaptive, data-driven, and spatially informed preparedness strategies. This integrated approach helps address structural gaps and supports more effective responses to complex CBRNE threats [12]. Based on this background, the objectives of this study are: (1) to analyze the main challenges in the readiness of Indonesia's public health system to address CBRNE threats, and (2) to formulate strengthening strategies that integrate health, technology, and institutional aspects to enhance national preparedness [13]. The findings are expected to contribute both conceptually and practically to the development of a more resilient health system and to support adaptive policymaking in response to future CBRNE threats [14].

The novelty of this study lies in its development of an integrated health, technology, and governance framework that treats CBRNE preparedness as a unified socio-technical system rather than a set of separate sectoral issues [15]. Unlike previous studies that focus only on health, security, or technology, this research combines these dimensions into a single analytical model supported by qualitative data and NVivo based analysis. It also incorporates a spatial perspective through GIS to highlight disparities in risk and capacity. This integrative and interdisciplinary approach provides a more comprehensive understanding of preparedness and offers a practical model applicable to developing countries facing complex CBRNE challenges[16].

2. LITERATURE REVIEW

2.1. CBRNE Threats from a Public Health Perspective

Chemical, Biological, Radiological, Nuclear, and Explosives threats represent a multidimensional form of risk with significant implications for public health, the environment, and social stability. In a public health context, these threats are not only treated as emergency events but also as ongoing health risks that require integrated preventive, mitigation, and response strategies. Biological agents such as infectious pathogens, exposure to hazardous chemicals, and radiological contamination can lead to complex long term health effects, including chronic illness, disability, and large-scale mortality. A public health approach to CBRNE emphasizes the importance of surveillance systems, early detection, laboratory capacity, and the readiness of healthcare facilities to manage surges in cases. In addition, risk communication and public education play a critical role in minimizing the impact of CBRNE events [4], [6].

2.2. Health System Resilience

The concept of health system resilience provides a key foundation for addressing CBRNE threats. The World Health Organization (WHO) defines a resilient health system as one that can absorb shocks, adapt to changing conditions, and continue to deliver essential health services during crises. This resilience is supported by several core components, including the health workforce, financing, health information systems, logistics and supply chains, and governance. In the context of CBRNE, resilience is not only determined by service capacity but also by the system's ability to integrate technology, strengthen cross-sector coordination, and respond effectively to complex and uncertain threats [17], [18].

2.3. Integration of Technology and Engineering in CBRNE Management

Advances in technology and engineering play a critical role in strengthening preparedness for CBRNE threats. Technologies such as early warning systems, environmental sensors, Geographic Information Systems (GIS), and digital health information systems enable real-time risk monitoring and data-driven decision-making. These technologies also improve efficiency in logistics distribution, crisis management, and inter-agency coordination. From an interdisciplinary perspective, this approach connects health sciences with engineering and applied sciences, resulting in more adaptive and effective response systems [19], [20].

2.4. Governance and Cross-Sector Coordination

Effective management of CBRNE threats requires cross-sector collaboration involving government institutions, healthcare systems, the military, and disaster management agencies. Effective governance is characterized by clear regulatory frameworks, integrated coordination mechanisms, and well-defined institutional roles. However, in many cases in Indonesia, key challenges include fragmented policies, limited system interoperability, and insufficient coordination among stakeholders. These conditions highlight the need for governance models that are capable of integrating diverse capacities and interests within a comprehensive and coherent framework [21], [22].

2.5. Research Gap

Although a substantial body of research has examined CBRNE from security and technological perspectives, studies that explicitly integrate CBRNE threats into public health systems remain limited, particularly in developing country contexts such as Indonesia. Existing approaches also tend to be fragmented across health, technology, and policy dimensions, resulting in an incomplete understanding of system readiness. This gap indicates the need for a more comprehensive and interdisciplinary framework that combines these three dimensions into a unified analytical approach to strengthen public health preparedness for CBRNE threats [23], [24].

2. MATERIALS AND METHODS

3.1. Analytical Framework

This study applies an integrated analytical framework developed from the literature by linking four key dimensions: CBRNE threats from a public health perspective, health system resilience, technology and engineering integration, and governance and cross-sector coordination. These dimensions are not only used as theoretical references but are operationalized to guide the data analysis process. The concept of CBRNE threats is used to identify risk characteristics and their implications for the health system, particularly in terms of surveillance, early detection, service capacity, and risk communication. The health system resilience framework is applied to evaluate the system's ability to absorb shocks, adapt, and respond to threats, focusing on human resources, information systems, logistics, and governance[25]. The technology and engineering dimension is used to examine the role of technological support, including early warning systems, laboratory capacity, and health information systems. Meanwhile, the governance dimension is applied to assess policy integration, institutional roles, and cross-sector coordination, including civil-military collaboration. These dimensions are integrated into the qualitative analysis using NVivo through open coding, axial coding, and selective coding. This process produces key themes such as governance fragmentation, disparities in health system capacity, technological limitations, lack of operational standardization, and the need for system integration. The framework enables a systematic and interdisciplinary analysis by linking health, technology, and governance in understanding CBRNE preparedness[26]

3.2. Research Design

This study employs a qualitative approach with a descriptive design. This approach was selected to capture in-depth insights into complex phenomena related to the readiness of the health system in addressing CBRNE threats. The descriptive design allows for a comprehensive understanding of context, dynamics, and the relationships among factors influencing system preparedness[27].

3.3. Data Sources and Collection Techniques

Data were obtained from multiple sources to ensure comprehensiveness. Primary data were collected through in-depth interviews with experts in public health, CBRNE, and health policy. Direct observations were conducted in Indonesia to identify actual practices within the health system related to preparedness. In addition, a literature review was carried out, including national regulations and policy documents. Secondary data were obtained from online media, official reports related to CBRNE incidents and preparedness in Indonesia, and scientific publications. This approach enables source triangulation to strengthen the validity of the findings[28].

3.4. Research Setting

The study focuses on the national context of Indonesia, with particular attention to public health systems involved in preparedness and response to CBRNE threats. This setting was selected due to Indonesia's high vulnerability to both natural and non-natural hazards.

3.5. Data Analysis Technique

Data were analyzed using Creswell's qualitative analysis model, which consists of three stages: (1) open coding to identify initial concepts and categories, (2) axial coding to group categories into broader themes, and (3) selective coding to construct the main narrative based on relationships among themes[28]. NVivo software was used to support the analysis process, including data organization, coding, and visualization of relationships among concepts. This approach allows for a systematic, transparent, and data-driven analysis.

3.6. Validity and Trustworthiness

To ensure the credibility of the findings, this study applies triangulation techniques, including source triangulation, methodological triangulation, and researcher triangulation through discussions among researchers. In addition, member checking was conducted to ensure consistency between the researcher's interpretation and participants' perspectives.

3.7. Interdisciplinary Approach

This study adopts an interdisciplinary approach by integrating perspectives from public health, engineering, and governance. This approach is intended to produce a comprehensive analysis that is relevant to addressing the complex and multidimensional nature of CBRNE threats.

3.8. Ethical Considerations

This study adhered to established ethical research standards, ensuring that all participants were fully informed about the purpose, procedures, and potential risks of the research before their involvement. Informed consent was obtained voluntarily, and participants were assured of their right to withdraw at any time without consequences. Confidentiality and anonymity were strictly maintained, with all data securely stored and used solely for research purposes. Additionally, the study complied with institutional ethical guidelines and respected participants' rights and well-being throughout the research process[29].

4. RESULTS AND DISCUSSION

4.1 Results

4.1.1 In-depth Interviews

Based on in-depth interviews with 17 experts in public health, CBRNE, and health policy from relevant ministries in Indonesia, the findings indicate that the readiness of Indonesia's public health system to address CBRNE threats remains limited. Informants emphasized that governance and regulatory frameworks are still fragmented and have not yet formed an integrated operational system. In addition, cross-sector coordination, including civil-military integration, is not yet functioning systematically, particularly in complex emergency scenarios. Experts also highlighted that risk communication has not been prioritized, which may lead to misunderstandings and public panic during incidents[30].

4.1.2 Field Observations

Direct observations conducted in referral hospitals and primary healthcare facilities in Jakarta, West Java (Bandung and surrounding areas), as well as selected coastal and island regions, reveal that health system capacity for responding to CBRNE threats remains uneven. Key limitations include the absence of dedicated decontamination facilities, the lack of standardized CBRNE triage systems, and insufficient competencies among healthcare personnel in handling chemical, biological, radiological, and nuclear exposures. Most healthcare facilities still rely on general emergency procedures without specific CBRNE protocols, particularly outside major referral hospitals[31]. These findings are reinforced by several cases in Indonesia. In the chemical domain, toxic gas leak incidents in industrial areas such as Cilacap (ammonia) and Gresik demonstrate that nearby health facilities are not fully prepared to conduct rapid decontamination and manage hazardous chemical exposure. In the biological domain, the COVID-19 pandemic revealed that, despite later improvements, the system was initially unprepared for a sudden surge in cases and rapid cross-sector coordination[32]. In the radiological domain, incidents involving uncontrolled radioactive sources, such as the contamination case in Batan Indah, South Tangerang (2020), indicate that health responses still rely heavily on technical agencies such as BAPETEN and are not yet fully integrated into the general healthcare system[33]. Overall, these observations suggest that operational readiness in the field remains partial and lacks national standardization, resulting in suboptimal responses to CBRNE threats, particularly in regions with limited resources and infrastructure.

4.1.3 Literature Review of Regulations and National Policies

The review of national regulations shows that Indonesia has established several legal frameworks related to disaster management and health emergencies; however, these remain sectoral in nature. For instance, Law No. 24 of 2007 on Disaster Management, Article 5 assigns responsibility to the government for disaster management, while Article 26(1) guarantees the public's right to protection from disasters. However, this law focuses on general disaster management and does not specifically address CBRNE threats. Similarly, Law No. 6 of 2018 on Health Quarantine, Article 4 states that both central and local governments are responsible for protecting public health from risk factors that may lead to public health emergencies, while Article 9(1) regulates quarantine measures at points of entry and within territories. Although relevant to biological threats, this law primarily focuses on infectious disease control and does not comprehensively integrate chemical, radiological, and nuclear risks. Law No. 36 of 2009 on Health, particularly Article 152, regulates the management of outbreaks and extraordinary events, while Article 154 emphasizes the government's responsibility in addressing health problems arising from disasters. However, its scope remains general and does not include specific operational standards for CBRNE incidents, which require multidisciplinary and technology-intensive approaches.

In addition, Government Regulation No. 21 of 2008 on Disaster Management Implementation, particularly Article 6, outlines disaster management phases, including pre-disaster, emergency response, and post-disaster stages. Nevertheless, this regulation does not explicitly integrate health response systems, detection technologies, and cross-sector coordination in the context of CBRNE. Overall, although these regulations address disaster management, health, and quarantine separately, they operate within sectoral mandates. There is no comprehensive regulatory framework that integrates health, security, technology, and cross-sector coordination into a unified national CBRNE operational system, indicating a gap between existing policies and the requirements of a risk-based preparedness system.

4.1.4Secondary Data (Media, Official Reports, and Scientific Publications)

The analysis of secondary data derived from national media, institutional reports, and scientific publications reveals a consistent pattern of challenges in Indonesia's preparedness for CBRNE (Chemical, Biological, Radiological, Nuclear, and Explosives) threats. Overall, these findings indicate that the primary issues are not solely related to resource availability, but also to limitations in system integration, technical capacity, and cross-sector coordination. From a technological and information systems perspective, multiple sources suggest that Indonesia still faces constraints in developing integrated early warning and rapid response systems. Existing systems tend to operate in a fragmented, sectoral manner, resulting in limited data sharing and a lack of real-time accessibility across institutions. This fragmentation affects the speed and accuracy of decision-making, particularly in emergency situations that require timely, data-driven responses. These issues are highlighted in official reports from BNPB and BAPETEN, including the radiological incident in Batan Indah (2020), which exposed delays in technical coordination and data integration across agencies.

In terms of laboratory capacity, limitations are evident in the ability to detect, identify, and analyze CBRNE threats quickly and accurately. Laboratory capabilities remain uneven, both in terms of infrastructure and human resources, thereby constraining the effectiveness of national health surveillance systems. Evidence from scientific publications on Indonesia's COVID-19 response further indicates that surveillance and reporting systems were not fully integrated at the national level, particularly regarding data interoperability and response speed. This suggests that the challenges are structural in nature and persist across different types of public health emergencies.

Furthermore, media reports on industrial chemical leaks and public health incidents provide additional support for these findings by illustrating the gap between operational demands in the field and the existing technological and infrastructural readiness. Media coverage serves as an important triangulation source, demonstrating how these limitations translate into delayed responses and suboptimal risk mitigation at the community level.

In conclusion, the synthesis of these secondary sources underscores that Indonesia's preparedness for CBRNE threats still requires significant strengthening, particularly in the integration of information systems, enhancement of laboratory capacity, and utilization of technology for real-time risk monitoring. Addressing these challenges necessitates a more integrated approach that connects health system capacity, technological support, and collaborative governance within a science- and technology-based public health response framework.

4.1.5 Data Analysis Using Creswell's Model and NVivo

In this study, data analysis was conducted using Creswell's qualitative analysis model, supported by NVivo software, to systematically examine CBRNE threats and the readiness of Indonesia's public health system. The analytical process was designed to integrate multiple data sources, including in-depth interviews, field observations, policy and regulatory documents, institutional reports, scientific publications, and relevant online media. The first stage involved organizing and preparing all collected data to ensure consistency, completeness, and suitability for qualitative analysis. Interview transcripts, observational notes, policy documents, and secondary sources were subsequently imported into NVivo and categorized according to their respective data sources.

The coding process combined inductive and deductive approaches. Deductive coding was guided by the study's analytical framework, particularly the dimensions of health system capacity, technological infrastructure, governance, cross-sector coordination, and risk communication. Inductive coding was simultaneously applied to identify emerging concepts and patterns that were not predetermined by the theoretical framework. Initial codes were progressively grouped into broader categories through open coding, axial coding, and selective coding. This process enabled the identification of key themes, including fragmented governance, disparities in healthcare capacity, limitations in technological infrastructure, laboratory preparedness, insufficient operational standardization, weak risk communication, and the need for integrated CBRNE preparedness.

Following Creswell's analytical procedures, the data were further reduced, categorized, compared, and interpreted to identify relationships among the emerging themes. NVivo supported this process by facilitating systematic data management, retrieval of coded segments, cross-source comparison, and visualization of thematic relationships. Word frequency analysis and text search queries were used to identify dominant concepts and examine their contextual associations. Word clouds provided an overview of frequently occurring terms, while hierarchy charts illustrated the relative prominence of major themes within the dataset. Thematic mapping was also used to explore connections among health, technology, operational preparedness, and governance dimensions.

Finally, the findings were interpreted through an interdisciplinary perspective to explain how structural, technological, institutional, and operational factors influence national CBRNE preparedness. Triangulation across interviews, observations, regulatory documents, and secondary data strengthened the credibility of the analysis. This analytical approach provided a comprehensive and transparent understanding of existing preparedness gaps and supported the formulation of integrated strategies for strengthening Indonesia's public health response to complex CBRNE threats.

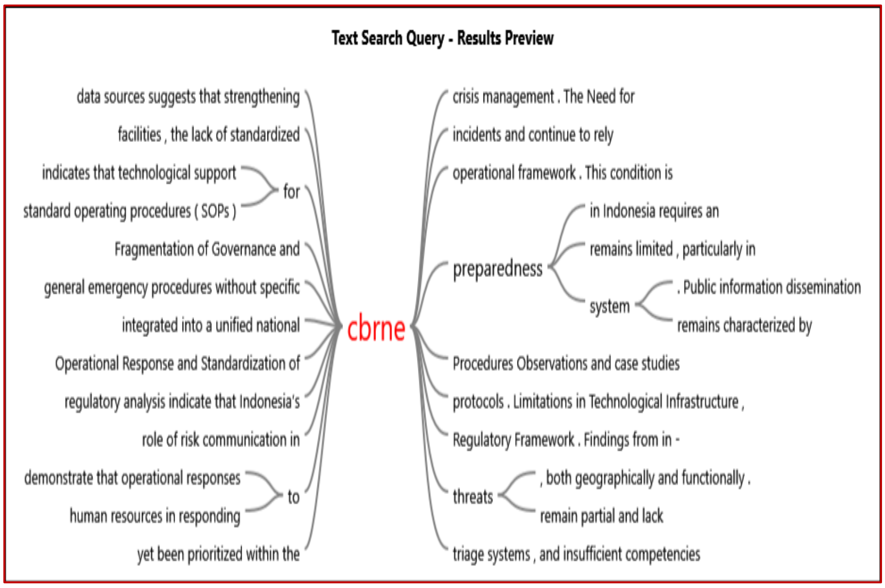

Figure 1. NVivo 12 Text Search Query Analysis

The figure presents the results of a *text search query* conducted using NVivo 12 with the keyword "CBRNE," visualized through a *word tree* structure. This visualization illustrates the contextual relationships of the term across multiple data sources, including in-depth interviews, field observations, regulatory documents, and secondary data. From a science, engineering, and health systems perspective, the analysis provides insight into how CBRNE-related issues are distributed across governance, operational, technological, and public health dimensions. The results indicate that the term CBRNE is most frequently associated with several major thematic clusters. First, the preparedness dimension remains limited, particularly within public health systems and risk communication mechanisms. This reflects gaps in health system resilience and the insufficient integration of public health preparedness strategies with community-level information dissemination. Second, the operational framework dimension reveals that incident responses still rely on general emergency procedures rather than specialized CBRNE protocols, indicating the absence of standardized, science-based operational systems[25].

Third, the analysis highlights the fragmentation of governance and regulatory frameworks, where existing policies operate within sectoral boundaries without forming a unified national CBRNE system. This finding is closely related to institutional and policy design challenges within complex socio-technical systems. Fourth, the results emphasize limitations in technological infrastructure and information systems, including delayed reporting, lack of real-time data integration, and insufficient utilization of digital health and monitoring technologies. From an engineering perspective, this reflects gaps in system interoperability and data-driven decision-making. Additionally, the analysis identifies capacity constraints in healthcare facilities and human resources, including the absence of CBRNE-specific triage systems, limited technical competencies among healthcare personnel, and unequal distribution of resources across regions. These findings demonstrate the need for strengthening both biomedical capabilities and health service delivery systems. Furthermore, the persistence of non-standardized operational responses indicates that existing practices have not yet incorporated integrated protocols supported by scientific and technological advancements[26].

Overall, the text search query results confirm six core themes: (1) fragmented governance, (2) disparities in health system capacity, (3) limitations in technology and information systems, (4) lack of standardized operational procedures, (5) insufficient risk communication, and (6) the need for system integration. These findings underscore that CBRNE preparedness in Indonesia represents a multidimensional challenge that requires the integration of health sciences, engineering systems, and evidence-based policy frameworks. Consequently, strengthening preparedness must involve the development of integrated health technologies, interoperable information systems, and coordinated governance models to support a more resilient and adaptive public health response system[34].

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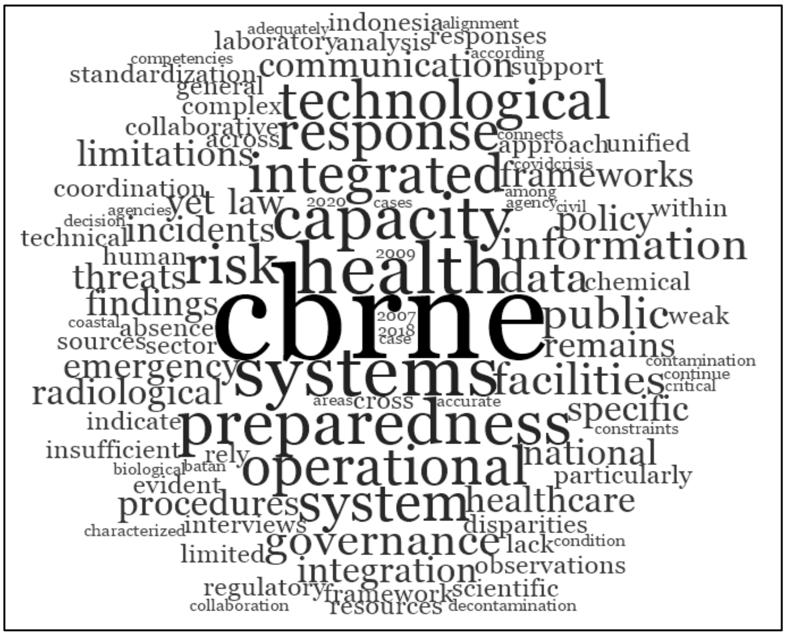

Figure 2. NVivo 12 Word Cloud

The figure presents a *word cloud* generated from NVivo 12 based on the full dataset, including interview transcripts, field observations, regulatory documents, and secondary sources. In this visualization, word size reflects frequency, meaning that larger words indicate concepts that appear more consistently across the data. The term “CBRNE” appears as the most dominant keyword, confirming that the analysis is strongly centered on chemical, biological, radiological, and nuclear threats within the public health context. Other prominent terms such as “health,” “system,” “preparedness,” “capacity,” and “risk” suggest that the discussion is primarily framed around health system readiness and risk management.From a health perspective, the frequent appearance of “health,” “healthcare,” and “facilities” points to the central role of healthcare infrastructure in responding to CBRNE incidents. At the same time, terms such as “technological,” “information,” “data,” and “systems” indicate that preparedness is closely linked to the availability of technological support, data integration, and information systems. This highlights the importance of system interoperability and data-driven decision-making in managing complex threats[35].

Governance-related terms, including “governance,” “policy,” “regulatory,” and “integration,” appear repeatedly, reflecting the importance of institutional coordination and regulatory frameworks. However, the presence of words such as “limitations,” “lack,” “insufficient,” and “weak” suggests that these systems are not yet functioning optimally and continue to face structural and operational constraints. Operational aspects are also evident through terms like “operational,” “procedures,” and “standardization,” indicating ongoing challenges in developing consistent and specialized response protocols. Meanwhile, the appearance of “communication” and “public” highlights the role of risk communication, particularly in shaping public awareness and response during emergencies. The inclusion of terms such as “radiological,” “chemical,” and “biological” further confirms that the analysis captures the full spectrum of CBRNE threats[36].

The word cloud highlights the complexity of CBRNE preparedness in Indonesia by revealing the prominence of key terms related to health systems, technology, governance, and social dynamics. This distribution of dominant concepts suggests that preparedness is not confined to a single sector but involves the interaction of multiple subsystems that must function cohesively. The frequent appearance of terms associated with health infrastructure indicates the central role of public health capacity, including surveillance, response readiness, and service delivery. At the same time, the visibility of technological elements reflects the importance of digital systems, early warning mechanisms, and data integration in supporting timely decision-making. Equally important is the presence of governance-related terms, which underscores the role of institutional coordination, regulatory frameworks, and inter-agency collaboration in managing complex risks. Social factors appearing in the word cloud further point to the significance of community engagement, risk communication, and public awareness in strengthening overall resilience. Together, these dimensions illustrate that existing challenges stem from fragmentation across sectors, limited interoperability of systems, and uneven coordination mechanisms.

Therefore, improving CBRNE preparedness requires an integrated framework that aligns health services, technological capabilities, and governance structures. Such an approach would enable more efficient data sharing, faster response times, and more coordinated actions, ultimately enhancing national resilience against multidimensional threats[37].

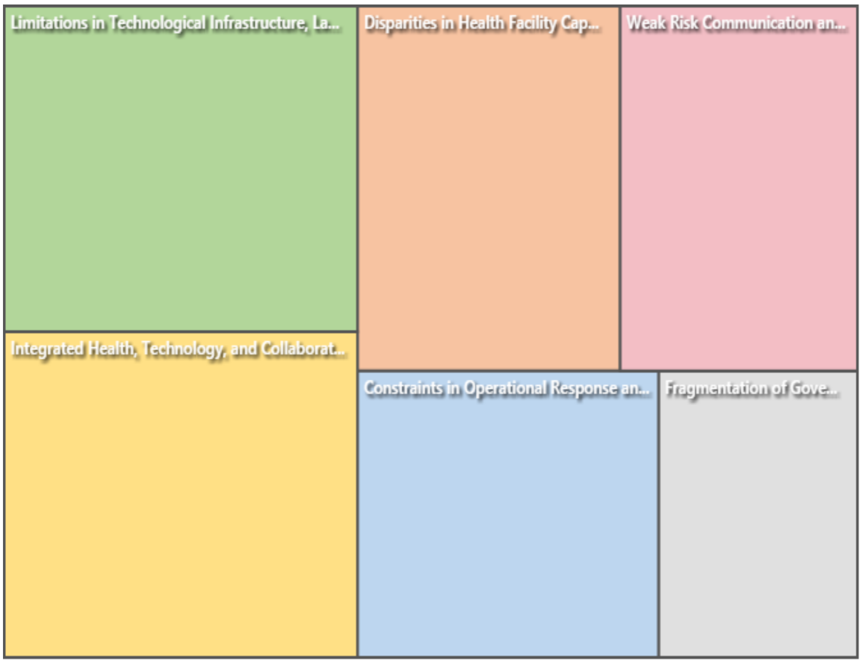

Figure 3. NVivo 12 Hierarchy Chart Analysis

The figure presents a hierarchy chart generated from NVivo 12, illustrating the relative weight of key themes identified in the study. Each block represents a coded theme, and its size reflects the proportion of references or coding density within the dataset. This visualization provides a comparative overview of how frequently each theme appears across interviews, observations, regulatory analysis, and secondary data. The largest segments are associated with "Limitations in Technological Infrastructure" and "Disparities in Health Facility Capacity," indicating that these two themes dominate the dataset. This suggests that the most critical challenges in CBRNE preparedness are related to technological gaps such as limited data integration, laboratory capacity, and information systems and uneven healthcare capacity across regions. These findings highlight systemic weaknesses in both the technical and service delivery dimensions[38].

A similarly prominent area is "Integrated Health, Technology, and Collaborative Governance," which appears as a major theme despite being conceptual in nature. Its prominence reflects a strong emphasis across data sources on the need for integration as a solution, linking health systems, technological infrastructure, and inter-agency coordination. This indicates that respondents and data sources consistently point toward integration as a strategic priority. The chart also shows substantial representation of "Constraints in Operational Response and Standardization," suggesting that procedural gaps and the absence of standardized CBRNE protocols remain a significant issue. This aligns with earlier findings that responses are still largely dependent on general emergency mechanisms rather than specialized systems. In contrast, "Fragmentation of Governance" and "Weak Risk Communication and Public Preparedness" appear with relatively smaller proportions. However, their presence remains significant, indicating that although these issues are less frequently mentioned, they still contribute meaningfully to the overall problem structure, particularly in shaping coordination and public response dynamics[39].

The hierarchy chart indicates that CBRNE preparedness in Indonesia is largely constrained by limitations in technology and institutional capacity, which form the core barriers to effective response. These constraints are further reinforced by fragmented governance structures, gaps in operational readiness, and challenges in communication across sectors. Together, these factors create a system that is not fully synchronized, reducing the ability to respond quickly and effectively to complex threats. At the same time, the prominence of integration as a key theme highlights the urgent need for a systems-based approach. Preparedness cannot rely on isolated improvements within individual sectors, but must instead focus on connecting health systems, engineering capabilities, and governance mechanisms into a unified framework. Such integration would enhance coordination, improve data sharing, and support faster, more informed decision-making. Ultimately, strengthening CBRNE preparedness requires not only technological upgrades but also institutional alignment and cross-sector collaboration to build a more resilient and adaptive national system[40].

4.1.6 Spatial Analysis of CBRNE Risk and Health System Capacity (GIS-Based Analysis)

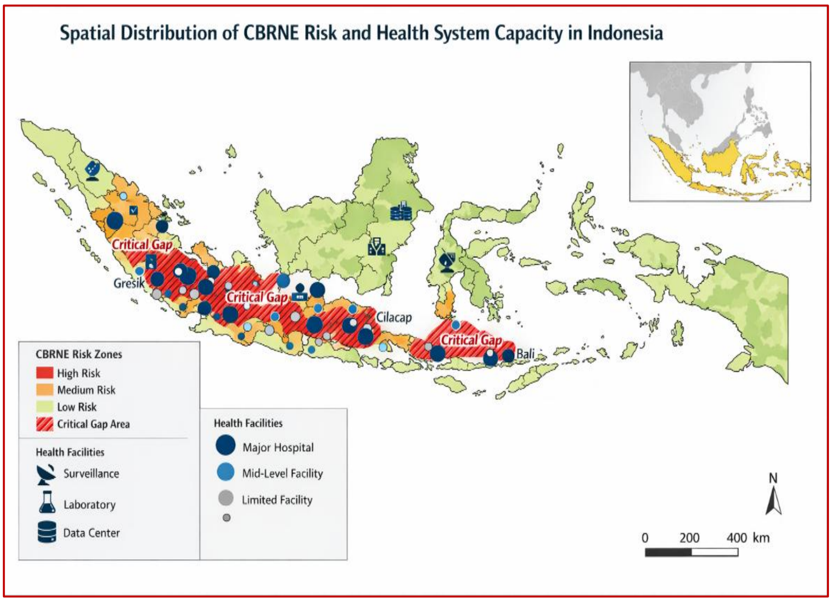

Figure 4. Geospatial Analysis of CBRNE Preparedness in Indonesia

The GIS-based analysis illustrates the spatial relationship between CBRNE risk exposure and the distribution of health system capacity across Indonesia, highlighting critical gaps where high-risk areas are not supported by adequate healthcare infrastructure and technological resources[41]. High-risk zones, particularly in industrial and densely populated regions such as Java, overlap with uneven availability of referral hospitals, laboratory capacity, and early detection systems, indicating structural weaknesses in preparedness[42]. From an interdisciplinary perspective aligned with Science, Engineering and Health Studies, this finding demonstrates the importance of integrating geospatial analysis, public health system capacity, and data-driven decision-making to support more effective resource allocation and risk management. The results suggest that strengthening CBRNE preparedness requires not only institutional and technological improvements but also spatially informed strategies to ensure equitable and timely responses across regions[43].

4.2Discussions

4.2.1 CBRNE Preparedness as a Socio-Technical System

The findings suggest that CBRNE preparedness in Indonesia should not be viewed solely as a public health issue, but rather as a socio-technical system involving the interaction between health capacity, technological infrastructure, and governance. From a health system resilience perspective, the limitations identified particularly in preparedness and response indicate that the system is not yet fully capable of absorbing and adapting to complex, high-impact threats. This reinforces the need for an integrated approach in which public health systems are supported by technological and engineering solutions to enable more adaptive and data-driven responses[44].

4.2.2 Gap Between Regulatory Frameworks and Operational Practice

The study reveals a clear gap between existing regulatory frameworks and their implementation in practice. Although Indonesia has established multiple policies related to health emergencies and disaster management, these remain sectoral and lack integration within a unified CBRNE framework. As a result, operational responses continue to rely on general emergency procedures rather than specialized protocols. From a systems perspective, this reflects weak integration between policy, operational mechanisms, and technical systems, limiting the effectiveness of coordinated responses[45].

4.2.3 Technological Constraints and Their Impact on System Performance

The prominence of technological limitations in the NVivo analysis highlights the critical role of infrastructure in CBRNE preparedness. Constraints in early detection systems, laboratory capacity, and data integration reduce the ability of the system to respond quickly and accurately. From an engineering standpoint, this points to insufficient interoperability across information systems and limited use of real-time monitoring and decision-support tools. Strengthening preparedness therefore requires not only policy reform but also investment in integrated health technologies and digital infrastructure[46].

4.2.4 Uneven Health System Capacity as a Structural Challenge

Disparities in healthcare capacity across regions represent a fundamental structural issue. The gap between well-equipped urban referral hospitals and under-resourced facilities in remote and coastal areas directly affects the system's ability to respond to CBRNE incidents. In a public health context, such disparities increase vulnerability and may lead to uneven health outcomes during crises. Addressing this issue requires a more spatially informed approach to resource allocation, supported by tools such as geospatial analysis and data-driven planning[47].

4.2.5 Lack of Standardized Operational Protocols

The absence of standardized CBRNE-specific procedures indicates that operational readiness remains incomplete. Many healthcare facilities continue to rely on general emergency protocols, which are not designed to handle the complexity of CBRNE incidents. From a systems design perspective, standardization is essential to ensure consistency, efficiency, and safety in response operations. Developing science-based and technically informed protocols is therefore a critical step toward improving operational performance.

4.2.6 Risk Communication as a Missing Link in Preparedness

The findings also highlight the limited role of risk communication within the current preparedness framework. Public information systems remain fragmented and often lack clarity, which can contribute to confusion and panic during emergencies. In public health practice, effective risk communication is essential for building trust, guiding public behavior, and supporting crisis management. Its absence suggests that the social dimension of preparedness has not yet been fully integrated into the broader system[48].

4.2.7 Integration as a Strategic Response

A key contribution of this study lies in identifying integration as the central requirement for strengthening CBRNE preparedness. The findings consistently point to the need for a framework that connects three main components: health system capacity, technological and engineering support, and collaborative governance. This integrated approach aligns with the interdisciplinary focus of SEHS and offers a pathway toward a more coherent and effective response system. By linking these elements, it becomes possible to develop a preparedness model that is not only technically robust but also operationally feasible and policy-relevant.

Overall, the study shows that CBRNE preparedness in Indonesia is constrained by gaps in system integration, technological capacity, and institutional coordination. Addressing these challenges requires an interdisciplinary approach that brings together health sciences, engineering systems, and evidence-based policy to build a more resilient and adaptive public health response system[49].

4.2.8 Implications of the Study

The findings of this study have important implications for policy, practice, and research in strengthening CBRNE preparedness. From a policy perspective, the results highlight the need for a more integrated regulatory framework that connects health systems, technological infrastructure, and cross-sector governance into a unified national strategy. Practically, the study underscores the importance of investing in healthcare capacity, including workforce competencies, laboratory systems, and early detection technologies, as well as improving interoperability of health information systems. The identification of spatial disparities through GIS also implies that preparedness strategies should be geographically targeted to ensure equitable resource allocation. From a research perspective, the integrated framework offers a foundation for future studies to further test and refine interdisciplinary approaches, particularly through the incorporation of quantitative methods and comparative analyses across different regions.

4.2.9 Strengths and Limitations of the Study

The strength of this study lies in its interdisciplinary approach that integrates public health, technology, and governance into a unified analytical framework, providing a more comprehensive understanding of CBRNE preparedness. The use of data triangulation from interviews, observations, regulatory analysis, and secondary sources enhances the credibility of the findings, while NVivo-based analysis ensures systematic and transparent qualitative interpretation. In addition, the incorporation of GIS introduces a spatial dimension that strengthens the applied science contribution and aligns with the interdisciplinary scope of the study. However, this study also has several limitations. As a qualitative descriptive study, the findings are context-specific and may not be fully generalizable to other settings. The reliance on expert judgment may also introduce subjectivity, and the absence of quantitative validation limits the ability to measure the strength of relationships among variables. Future studies are recommended to adopt mixed-method approaches and expand the analysis to broader regional contexts.

5. CONCLUSIONS

This study finds that the readiness of Indonesia's public health system to address CBRNE threats remains limited and shaped by a set of interconnected challenges. These include fragmented governance and regulatory frameworks, uneven distribution of healthcare capacity and human resources, and constraints in technological infrastructure, particularly in laboratory systems and health information integration. In addition, the absence of standardized CBRNE-specific operational procedures and the limited role of risk communication further reduce the system's ability to respond effectively. Weak coordination across sectors, including insufficient civil-military integration, reinforces these limitations. Taken together, these findings indicate that current preparedness is still developing and not yet equipped to manage complex, high-impact CBRNE events in a consistent and system wide manner.

In response to these challenges, the study proposes an integrated approach to strengthening CBRNE preparedness that brings together health system capacity, technological and engineering support, and collaborative governance. Strengthening efforts should focus on improving healthcare infrastructure and workforce competencies, while simultaneously advancing technology-based solutions such as early warning systems, integrated laboratory networks, and interoperable health information systems. At the institutional level, a more coordinated governance framework is needed to align policies, operational procedures, and cross-sector collaboration within a unified national system. This integrative model reflects the interdisciplinary orientation of science, engineering, and health studies, and offers both practical and conceptual contributions for developing a more resilient and adaptive public health system capable of addressing complex CBRNE threats.

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Dhiraj Kelly Sawlani	: Conceptualization, Investigation, Data Collection, Writing-Original Draft.
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Sutanto	: Methodology, Visualization, Validation, Writing-Review & Editing.
Faonaso Harefa	: Conceptualization, Formal Analysis, GIS Analysis, Visualization, Writing-Original Draft, Writing-Review & Editing.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the research, authorship, and publication of this article.

ETHICS STATEMENT

This study was conducted in accordance with established institutional ethical guidelines and research ethics principles. All participants were informed about the objectives, procedures, and potential risks of the study prior to participation. Informed consent was obtained voluntarily from all participants, who were also informed of their right to withdraw from the study at any time without consequences. Confidentiality and anonymity were strictly maintained, and all collected data were securely stored and used solely for research purposes. The rights, privacy, and well-being of all participants were respected throughout the research process.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to ethical and confidentiality considerations, data containing potentially identifiable participant information are not publicly available.

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