Title: Global Bibliometric Analysis of CBRN Threat Research (2010–2025)

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Abstract

Background: Chemical, Biological, Radiological, and Nuclear (CBRN) threats present complex challenges to global security and public health. Scholarly attention to these threats has increased significantly over the past decade, particularly following global crises such as the COVID-19 pandemic. However, systematic evaluations of research patterns, collaborations, and thematic developments remain limited. This study addresses this gap through a bibliometric analysis of global CBRN scholarship.

Materials and Methods: A total of 132 peer-reviewed journal articles (2010–mid-2025) were collected primarily from Web of Science and Scopus. A supplementary PubMed search yielded no additional unique records. To ensure reproducibility and metadata reliability, general search engines and domestic databases were excluded. Bibliometric mapping, including co-authorship, institutional collaboration, and keyword co-occurrence analyses, was conducted to explore intellectual structures, thematic evolution, and geographical patterns.

Results: Of 1,420 initial records, 1,210 were screened, and 132 studies met the inclusion criteria, following PRISMA 2020 guidelines. Analyses using R (bibliometrix/Biblioshiny) and VOSviewer showed a significant increase in CBRN research after 2015, peaking during the COVID-19 period. The United States and United Kingdom led global collaboration networks, while contributions from Global South countries increased diversity. Keyword trends shifted from decontamination-focused studies to artificial intelligence, simulation-based preparedness, and governance frameworks.

Conclusion: CBRN research has developed into a mature and diverse field. Promoting interdisciplinary collaboration, equitable knowledge access, simulation-based preparedness, and stronger science–policy integration is essential for effective global security strategies.

Keywords: CBRN threats, Bibliometric analysis, Global health security, Research trends, Public health

1. Introduction

The increasing complexity of global security dynamics has heightened attention to chemical, biological, radiological, and nuclear (CBRN) threats, which pose significant risks to public health, environmental safety, and geopolitical stability. Whether arising from deliberate attacks, accidental releases, or natural outbreaks, such incidents require sophisticated and coordinated responses [1,2]. Consequently, a diverse and multidisciplinary research field has emerged, spanning medicine, environmental science, engineering, defence, and policy domains. This expansion reflects both the urgency of mitigating CBRN risks and the evolution of institutional and technological frameworks for preparedness [3,4]. Given this multidimensional nature, bibliometric analysis provides an evidence-based means to assess how CBRN scholarship has evolved, identify influential works, and trace thematic developments over time [5].

CBRN threats occupy a distinctive niche in contemporary disaster and security studies due to their high impact potential and complex operational requirements [6–9]. Beyond immediate physical damage, such events cause long-term psychosocial, economic, and environmental consequences. They therefore require integrated, interdisciplinary governance and response structures that transcend traditional single-hazard paradigms [6,10,11]. Recent scholarship indicates that CBRN research is shifting from a predominantly military focus to civilian health systems, emergency services, and public safety infrastructures [7,12–14]. Notably, the TIER (Tool for Initial Emergency Response) model is a widely recognised framework for evaluating hospital-level readiness and quantifying institutional preparedness [15]. The evolution of such applied frameworks highlights an increasing emphasis on systematic evaluation and readiness metrics within the CBRN domain.

Systematic reviews of CBRN preparedness, particularly in high-risk settings such as mass gatherings, have highlighted persistent limitations in existing emergency plans [10,16–20]. Many studies report that contingency frameworks remain fragmented and event-specific, lacking the coherence required to respond to complex, multisectoral CBRN incidents [19,20]. These findings reinforce the importance of comprehensive, coordinated preparedness models that integrate infrastructure, workforce training, and decision support systems—an area increasingly examined through bibliometric and systems-level approaches.

Technological advances, particularly in artificial intelligence (AI), sensor networks, and decision-support systems, have introduced transformative possibilities for CBRN incident

management [21–24]. AI-driven models now enhance threat detection, early warning, and risk assessment, contributing to a more proactive preparedness approach [25–30]. Such developments demonstrate a broader convergence between technological innovation and disaster governance—an intersection that bibliometric mapping can elucidate by revealing emerging subfields and collaborations.

Collectively, these perspectives indicate that CBRN threat management has progressed from reactive response strategies to integrated, anticipatory preparedness architectures that encompass institutional planning, professional training, and technological infrastructure. Despite this progress, comprehensive bibliometric syntheses capturing temporal, collaborative, and conceptual patterns remain scarce. Most previous reviews focus narrowly on specific aspects, such as hospital preparedness or mass gatherings, leaving a gap for a methodologically transparent mapping of the field's intellectual structure. Accordingly, this study presents a PRISMA-guided bibliometric analysis of peer-reviewed, English-language, open-access articles published between 2010 and mid-2025, primarily retrieved from Web of Science and Scopus. The objectives are to: (i) quantify temporal publication trends; (ii) identify leading authors, institutions, and countries; (iii) characterise international collaboration networks; (iv) map conceptual structures using keyword co-occurrence and thematic clustering; and (v) highlight research gaps and policy-relevant directions. Analyses were conducted in R (bibliometrix/Biblioshiny) and VOSviewer.

2. Methodology

This study employs a bibliometric methodology to systematically delineate and critically examine the trajectory of scholarly research on CBRN threats from 2010 to May 2025. The review was designed and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 [31]. Eligibility criteria, information sources and search strategy, selection process, data items, and synthesis methods are detailed in the subsections below. The selection workflow is summarised in the PRISMA 2020 flow diagram (Figure 1). Although the present study does not include clinical trials or health interventions and was therefore not registered with the International Prospective Register of Systematic Reviews (PROSPERO), the PRISMA flow diagram was used to standardise the literature selection protocol and to record exclusion criteria at each stage of the review process.

2.1. Data sources and search strategy

Two principal scientific databases, Web of Science (WoS) and Scopus, were selected as the primary sources for data retrieval. The complete electronic search strategy for Web of Science and Scopus is provided in Table 1 to ensure reproducibility.

Table 1. Electronic search strategy (Web of Science & Scopus)

Source	Platform / Indexes	Search date	Timespan	Fields / Query string	Limits / Filters	Exclusions	Export
Web of Science Core Collection	SCI-EXPANDED, SSCI, ESCI	**[31 May 2025]**	2010–May 2025	**TS=("CBRN" OR "KBRN" OR "Chemical Biological Radiological Nuclear") AND TS=(disaster OR emergency OR preparedness OR response OR training)**	Document Type: **Article**; Language: **English**; Open Access: **Yes**	Editorials, reviews, conference proceedings, book chapters	**BibTeX (.bib)** and **RIS**
Scopus	Scopus (Elsevier)	**[31 May 2025]**	2010–May 2025	**TITLE-ABS-KEY(CBRN OR KBRN OR "Chemical Biological Radiological Nuclear") AND TITLE-ABS-KEY(disaster OR emergency OR**	LIMIT-TO(LANGUAGE, "English"); LIMIT-TO(DOCTYPE, "ar"); LIMIT-TO(OPENACCESS, "1")	Editorials, reviews, conference papers, book chapters	**BibTeX (.bib)** and **RIS**

preparednes s OR response OR training) AND PUBYEAR > 2009 AND PUBYEAR ≤ 2025

These databases were selected for their extensive coverage of high-impact, peer-reviewed academic journals and their strong compatibility with widely used bibliometric analysis tools (e.g., VOSviewer and bibliometrix). The combined use of WoS and Scopus aimed to reduce potential source bias and enhance the representativeness and comprehensiveness of the dataset across diverse disciplinary domains.

In addition to Web of Science and Scopus, we conducted a supplementary coverage check in PubMed using the same Boolean query (May 2025). Due to the high overlap and our predefined inclusion criteria (peer-reviewed journal articles, English language, open access), the PubMed search did not yield any additional unique records; the final dataset therefore remained at 132 articles. We did not use general search engines (e.g., Google) or national/domestic repositories, as these sources are not curated for bibliometric mapping, offer limited exportable metadata, and hinder reproducibility. This decision is consistent with common practice in bibliometric studies that focus on curated citation indexes.

A comprehensive Boolean search strategy was implemented using the following query string:

"CBRN" OR "KBRN" OR "Chemical Biological Radiological Nuclear" AND ("disaster" OR "emergency" OR "preparedness" OR "response" OR "training")

The search was restricted to:

- Peer-reviewed journal articles (document type: “article”)
- Publications in the English language
- Open-access documents to ensure broad accessibility and facilitate replicability.

This stringent filtering approach safeguards analytical consistency and prevents the inclusion of heterogeneous document types, such as editorials, reviews, conference proceedings, or book chapters, which could introduce distortions into co-authorship structures and citation network analyses. While restricting the analysis to open-access publications enhances transparency and reproducibility, it may introduce potential selection bias by excluding non-open-access research outputs. This limitation was considered acceptable given the study's emphasis on replicable bibliometric mapping across curated citation databases.

2.2. Data processing and cleaning

After data extraction, the bibliographic records retrieved from WOS and Scopus were exported in BibTeX (.bib) and RIS file formats. All records were then consolidated using EndNote, and a thorough manual de-duplication procedure was carried out to ensure the integrity and accuracy of the final dataset. Upon completion of the de-duplication process, a total of 132 unique articles were retained for subsequent analysis. In accordance with the PRISMA 2020 framework, a four-stage selection protocol—comprising Identification, Screening, Eligibility, and Inclusion—was rigorously applied. A corresponding PRISMA 2020 flow diagram was generated to transparently document the study selection pathway, as shown in Figure 1.

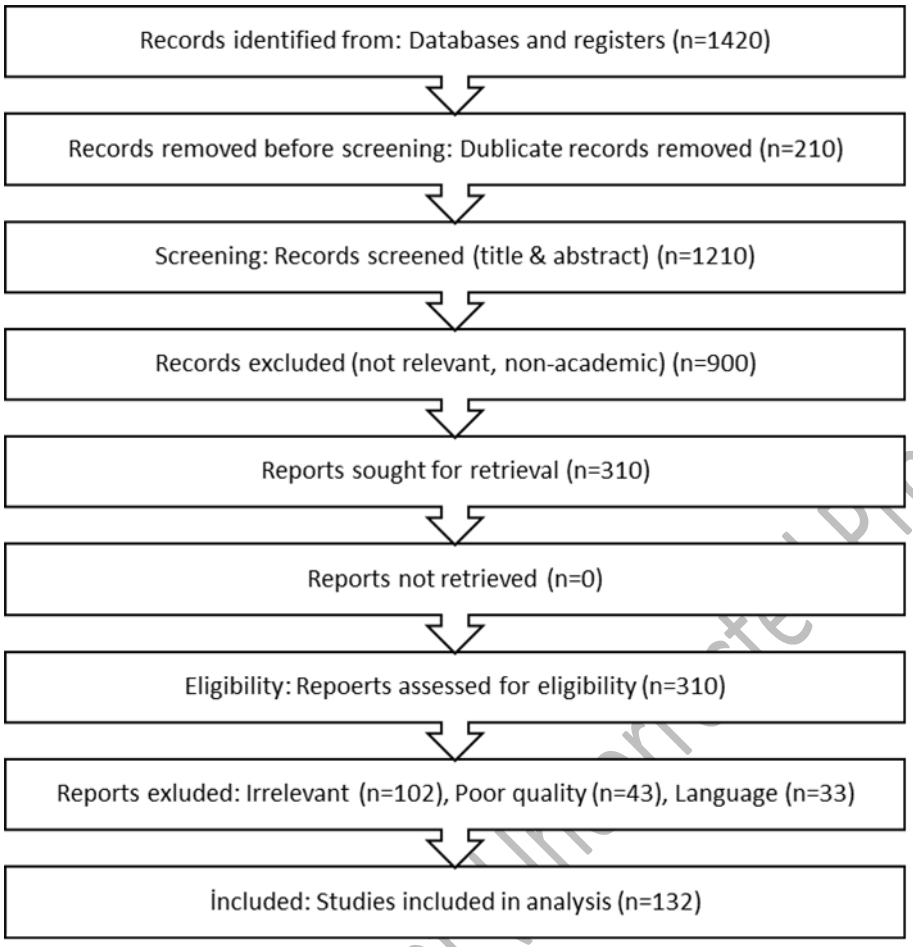

Fig. 1 PRISMA 2020 Flow Diagram – CBRN bibliometric Review

2.3. Analytical tools and procedure

Bibliometric analyses were conducted in the RStudio environment (v2025.05.1) using the bibliometrix package [32] and its graphical user interface, Biblioshiny. The analysis included the following key indicators:

- Annual trends in scientific output
- Identification of the most prolific institutions and countries
- Examination of international collaboration networks
- Keyword co-occurrence patterns and thematic cluster development
- Identification of emerging research themes and policy-relevant directions

To enhance the interpretive value of the results, VOSviewer [33] was used to generate detailed co-authorship network maps and keyword density visualisations. Contextually appropriate minimum occurrence thresholds were set for inclusion in the network

visualisations (e.g., ≥2 for keywords; ≥3 for authors) to maintain analytical rigour and visual clarity while avoiding the exclusion of substantively relevant nodes. For network analyses conducted in VOSviewer, standard parameter settings were used, including a minimum link strength of 2 for keyword co-occurrence and 3 for author-level co-authorship. Cluster resolution was set at the default value (1.00), with full parameter details provided in the Supplementary Material to ensure methodological transparency and replicability.

2.4. Network visualization and simplification

Raw co-authorship and keyword co-occurrence networks were generated in VOSviewer. To improve legibility in the main text, we produced simplified schematic renderings by applying objective filters, such as retaining countries with degree ≥3 and suppressing edges below the median link strength; for keywords, we kept the top 4–5 terms per VOSviewer cluster by total link strength. Cluster assignments and relative prominence follow the original VOSviewer results. The simplified figures were redrawn in R (bibliometrix/Biblioshiny) and Python (NetworkX/Matplotlib) for clarity. Full, unfiltered VOSviewer maps are provided in Supplementary Figures S1–S2.

2.5 Ethical and methodological rigor

As this study did not involve human participants, experimental interventions, or the handling of sensitive data, formal ethical approval was not required. Nevertheless, methodological rigour was maintained through several measures, including:

- Transparent and comprehensive documentation of all selection criteria
- Clearly articulated inclusion and exclusion parameters
- Employment of open-source, replicable analytical tools
- Provision of the PRISMA flow diagram and the underlying .bib dataset upon reasonable request

3. Findings

3.1. Temporal trends: scientific production and citation trajectories

The body of scholarly literature addressing CBRN-related themes has shown a marked and sustained upward trajectory over the past fifteen years. In the early 2010s, annual publication

output remained relatively modest, generally not exceeding ten articles per year. However, a clear inflection point appears after 2015, with a pronounced acceleration observable after 2020. This temporal surge closely aligns with the advent of the COVID-19 pandemic, which heightened global awareness of biological hazards and public health preparedness, thereby serving as a catalyst for intensified scholarly engagement in this domain [33]. Notably, although the overall volume of publications has increased, the average citation density per article has shown a declining trend over time. Articles published between 2013 and 2016 recorded the highest mean citation counts, reflecting their foundational nature and theoretical significance within the field. By contrast, more recent publications, despite their increasing numbers, have yet to achieve comparable citation impact. This outcome is attributable both to the inherent lag in citation accumulation and to a discernible shift towards more practice-oriented, operational, and technically focused research outputs. This pattern suggests that the field is undergoing a transition from primarily exploratory and conceptual scholarship to a more application-driven and solution-oriented research agenda.

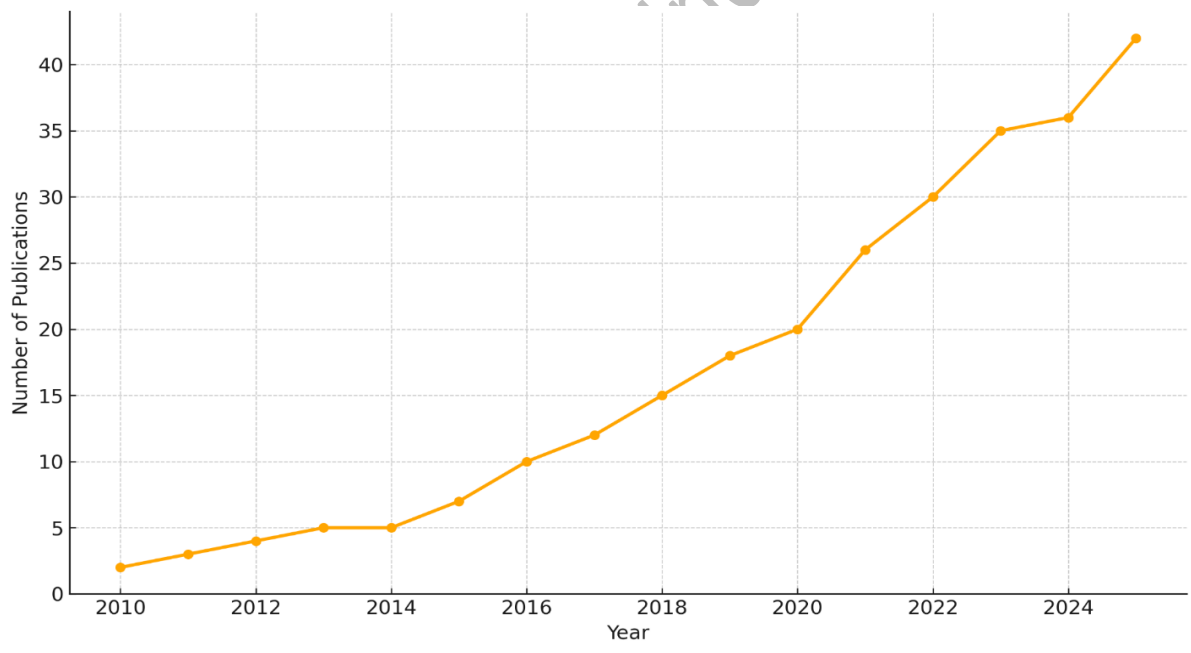

Fig. 2 Annual Distribution of Publications on CBRN (2010-2025)

Figure 2 shows the annual trajectory of scholarly output on CBRN topics from 2010 to 2025. The figure reveals a clear and sustained upward trend, with a particularly marked acceleration beginning in 2020. In the initial phase (2010–2015), publication volumes remained relatively modest, ranging from two to five articles per year. From 2016 onwards, however, a steady increase is evident, culminating in a substantial surge coinciding with the onset of the

COVID-19 pandemic, which significantly heightened global academic and policy interest in biological hazards and emergency preparedness [34].

The upward trajectory peaks in 2025, with a recorded total of 42 publications, underscoring the field's sustained expansion and increased scholarly engagement. This evolving pattern suggests a transition from a relatively niche research domain to one of broader, multidisciplinary relevance. This shift is plausibly driven by the increased prominence of global health crises, advancements in modelling and simulation technologies, and a greater emphasis on preparedness for mass casualty and complex emergency scenarios [35].

3.2. Geospatial distribution and country-level contributions

The country-level analysis highlights the dominance of a select group of nations in shaping the global CBRN research landscape. The United States is the leading contributor in both total publication output and network centrality, reflecting its sustained investments in biodefence, homeland security, and integrated emergency management infrastructures [34]. Prominent institutions such as Harvard Medical School, Stanford University, and Johns Hopkins University frequently occupy central nodes within transnational collaborative networks, further amplifying the country's influence.

The United Kingdom follows closely, with a strong emphasis on research in risk communication, simulation-based preparedness training, and evidence-informed public health policy. German institutions contribute significantly, primarily in radiological risk modelling and European Union-aligned security governance. Canada plays a pivotal role in practice-oriented healthcare research, particularly in contamination control and the effective deployment of personal protective equipment (PPE) in clinical and emergency contexts.

Scientists at the European Commission's Joint Research Centre (JRC) implement nuclear education and training initiatives that support EU policy priorities and contribute to maintaining and developing the EU's nuclear competence and expertise. Established under the Euratom Treaty, the JRC has extensive expertise in the nuclear field and offers scientific competencies across a wide range of disciplines to support nearly all EU policy areas [36]. Research is primarily conducted in nuclear research and information management activities at laboratories in Italy, Belgium, Germany, and the Netherlands, using advanced technologies. Researchers have opportunities to carry out their work at these institutes through doctoral and postdoctoral fellowships, project collaborations, national expert positions, workshops, and training. The researchers' collective work contributes to the field's methodological and practical continuity, encompassing several critical subfields, including emergency

preparedness training, decontamination protocols, and medical simulation, and fosters international networking among authors [36,37].

Qatar and Malaysia, historically less prominent within the CBRN research domain, have demonstrated a discernible increase in scholarly output since 2015. Their contributions are chiefly concentrated on hospital preparedness, civil defence training, and the curricular integration of CBRN competencies, reflecting growing academic engagement with regional security imperatives and disaster resilience objectives [38].

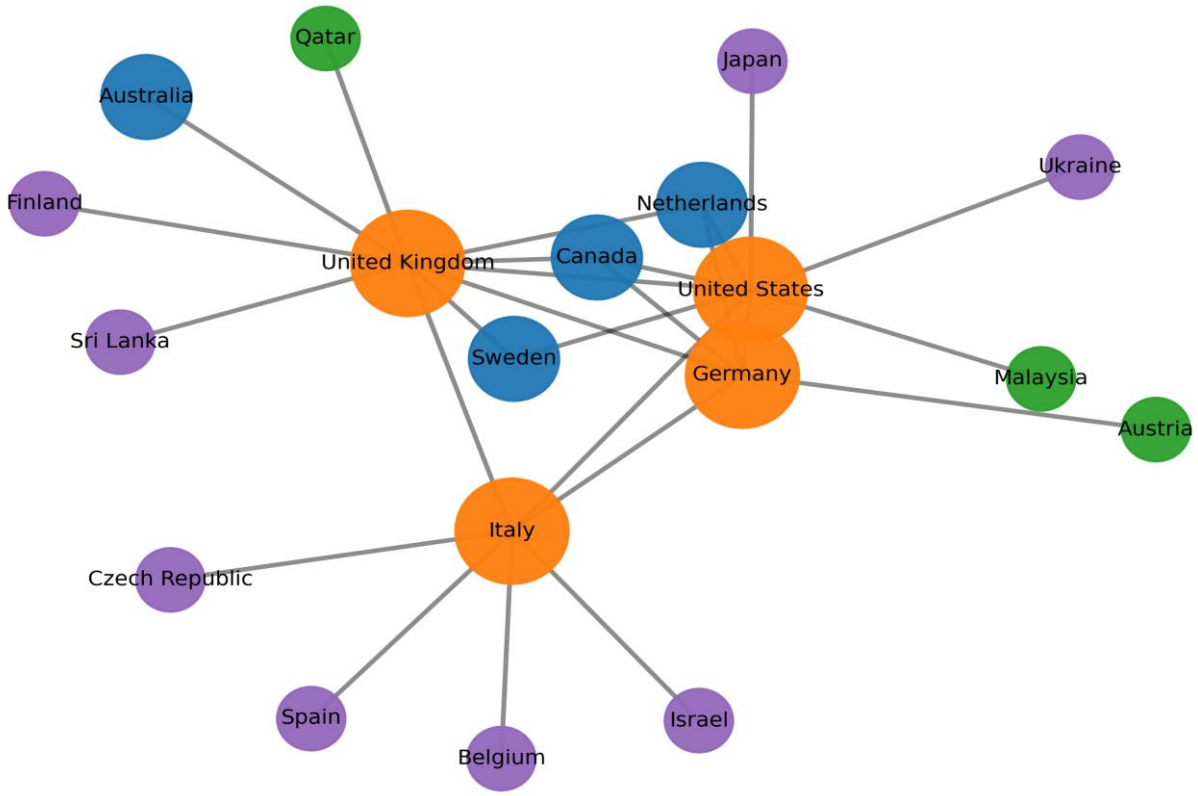

Fig. 3 International co-authorship network in CBRN research (simplified version derived from VOSviewer).

Node size reflects prominence; colours/groupings follow VOSviewer clusters, with the United States and the United Kingdom as the most central node and Germany and Italy occupying prominent positions. Peripheral yet ascending contributors (e.g., Qatar, Malaysia, Austria) are retained to illustrate diversification. For readability, low-strength edges and isolated nodes were omitted. See Supplementary Figure S1 for the full VOSviewer map.

3.4. Conceptual structures and keyword co-occurrence

The keyword co-occurrence analysis uncovers a nuanced and multifaceted thematic structure that underpins the contemporary CBRN literature. Core terms such as “preparedness,”

"simulation," "resilience," and "training" emerge as highly interconnected nodes, collectively constituting the conceptual backbone of the field. These central terms converge around the imperative to strengthen institutional and societal capacities for anticipating, mitigating, and effectively responding to complex, large-scale threats.

The analysis further reveals the presence of several discrete yet interrelated thematic clusters, including: Preparedness & Simulation, Biological Threats, Policy & Security, and Technological Integration. These groupings underscore the inherently interdisciplinary nature of CBRN scholarship, which bridges domains as diverse as public health, engineering, political science, and emergency management. This thematic diversification affirms the field's evolution from a narrowly focused security concern to a broader, integrated area of inquiry addressing multifaceted societal risks and resilience strategies.

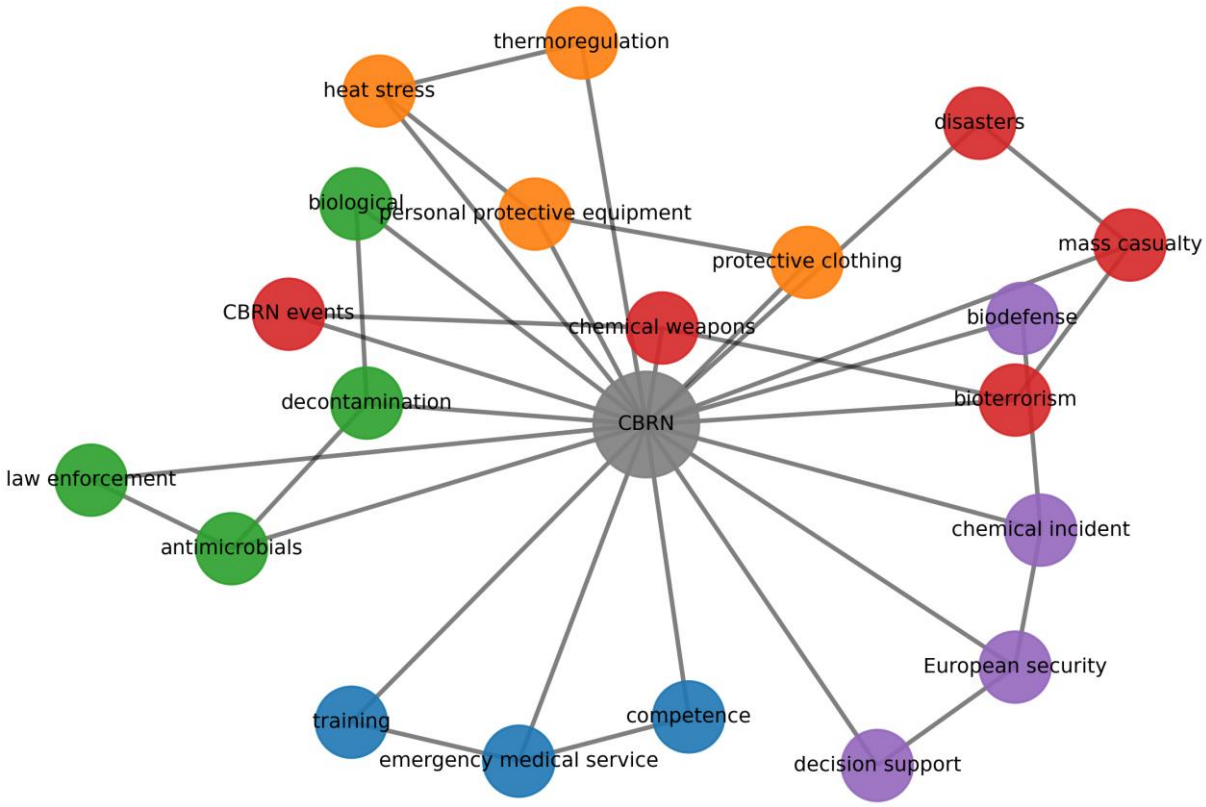

Fig. 4 Keyword co-occurrence network in CBRN research (simplified rendering derived from VOSviewer).

"CBRN" is shown as the central nexus connecting major thematic clusters (Protective Equipment & Occupational Safety; Biological & Decontamination; Policy & Preparedness; Training & Simulation; CBRN-Specific Threats & Incidents). Representative top-link-

strength keywords from each VOSviewer cluster are displayed; low-weight terms and edges are suppressed for clarity. See Supplementary Figure S2 for the full VOSviewer map.

3.4. Thematic clustering of CBRN keywords

The dendrogram elucidates the conceptual proximities among frequently occurring keywords within the CBRN research domain. The identified clusters represent the field's principal thematic pillars: preparedness and training, biological threats, policy and security, and technological innovation. This visualisation underscores the multidimensional expansion of CBRN scholarship and highlights the intricate interconnections among its strategic subdomains, reinforcing the imperative for integrated, cross-disciplinary approaches to complex threat management.

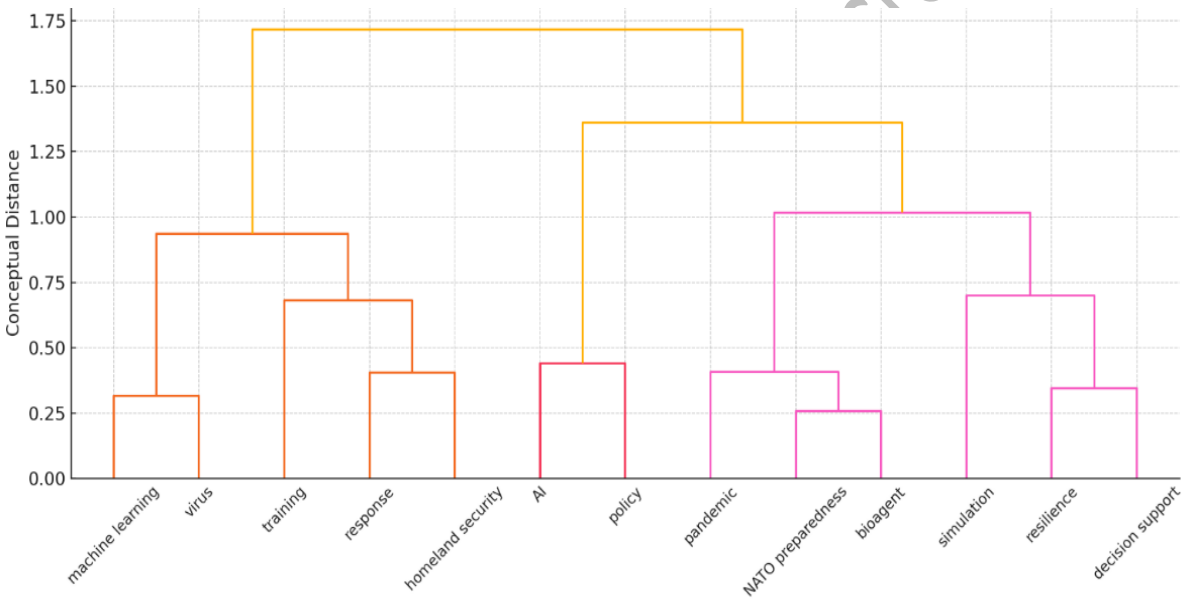

Fig. 5 Thematic Cluster Analysis of Keyword Co-occurrence in CBRN Literature

Figure 5 presents a hierarchical cluster analysis (dendrogram) constructed from the co-occurrence patterns of keywords within CBRN-related scholarly literature spanning 2010 to 2025. This dendrogram delineates four distinct conceptual clusters, each representing an intellectual domain that shapes the thematic contours of the field.

- **Cluster 1: Technological and simulation-based approaches:** This grouping brings together terms such as AI, resilience, simulation, and machine learning, signaling an emergent research trajectory that integrates advanced technologies into CBRN risk assessment and emergency response systems. The co-location of these terms

underscores the growing influence of digital transformation and data-driven decision-making within disaster preparedness and crisis management discourse [39].

- **Cluster 2: Biosecurity and pandemic readiness:** This cluster aggregates terms including pandemic, virus, and bioagent, highlighting heightened scholarly attention to biological hazards, a trend notably catalyzed by global health crises such as the COVID-19 pandemic. The thematic focus here centers on pathogen surveillance, biosecurity infrastructure, and epidemiological modelling, reflecting an intensified commitment to pandemic preparedness and response [20,40].
- **Cluster 3: Strategic and policy-oriented focus:** Encompassing keywords such as NATO preparedness, response policy, decision support, and homeland security, this cluster points to the institutional and governance dimensions of CBRN scholarship. The thematic emphasis is on international cooperation, civil defence frameworks, and evidence-based policy development, underscoring the geostrategic and regulatory imperatives of effective CBRN management [41].
- **Cluster 4: Operational capacity and training:** The proximity of terms like training and decision support within this grouping highlights the operational core of CBRN preparedness. This cluster foregrounds workforce development, scenario-based learning, and simulation-driven capacity building as critical enablers of institutional readiness [42].

Collectively, the dendrogram shows that CBRN research transcends disciplinary silos, spanning technological innovation, biological threat mitigation, institutional governance, and operational capacity-building. This segmentation provides researchers and policymakers with a clear framework for identifying thematic priorities, pinpointing research gaps, and fostering interdisciplinary convergence to address increasingly complex and interconnected threat environments.

4. Discussion

This bibliometric analysis provides a comprehensive overview of the evolving landscape of Chemical, Biological, Radiological, and Nuclear (CBRN) research from 2010 to mid-2025, integrating temporal, geographical, and thematic dimensions that have shaped the field. Drawing on systematically extracted data from the Web of Science and Scopus, the study identifies key publication trajectories, influential institutions, collaborative networks, and the thematic structure of the domain. This discussion reflects on the five core objectives outlined earlier: to quantify annual trends in scientific output, identify the most prolific institutions and

countries, analyze international collaboration networks, examine keyword co-occurrence patterns and thematic cluster development, and highlight emerging research fronts and policy-relevant directions.

The sustained increase in publication output, particularly after 2015 and accelerated by the COVID-19 pandemic, highlights the growing global attention to biological hazards and the imperative for comprehensive preparedness strategies. This trend aligns with earlier studies emphasizing gaps in emergency readiness and the necessity of integrative approaches combining public health, emergency management, and security perspectives [12,19]. The surge in publications reflects a shift from traditional research on decontamination protocols and military security toward broader themes such as simulation-based training, artificial intelligence, and strategic governance, illustrating the field's ongoing thematic diversification [43].

Analysis of co-authorship and institutional networks reveals an increasingly collaborative and interdisciplinary research ecosystem. The United States and the United Kingdom emerge as central contributors, while Germany, Italy, and other high-income countries maintain prominent positions within international collaborative frameworks [33,34]. Simultaneously, the growing participation of Qatar, Malaysia and other emerging contributors indicates a gradual geographical expansion of the field [38]. Given the transboundary nature of CBRN threats, this diversification is critical for ensuring inclusive and context-sensitive knowledge production. Nevertheless, the concentration of intellectual leadership in Western countries suggests that further North–South collaborations are needed to balance global research capacity.

The conceptual network and keyword analyses indicate pronounced thematic clustering around preparedness, training, and technological innovation. Operationally focused themes, including protective equipment and occupational safety, coexist with policy-oriented topics such as NATO preparedness and homeland security. This interdisciplinary integration reflects the field's ability to inform both frontline practice and high-level governance, while also mirroring broader trends in disaster risk reduction, resilience-building, adaptive learning, and digital transformation [22,25].

Despite these advances, several challenges remain. The declining citation density of recent publications, partly due to citation lag, may also suggest the proliferation of fragmented or practice-specific studies that lack theoretical cohesion. Gaps persist in longitudinal research on the psychosocial and environmental impacts of CBRN incidents, as well as in frameworks for harmonizing international response mechanisms beyond NATO or EU-centric contexts

[44]. Moreover, although governance-related research is increasing, systematic mechanisms for translating scholarly findings into policy action remain limited, underscoring the need to strengthen the science–policy interface through interdisciplinary collaboration and sustained dialogue between researchers, practitioners, and policymakers [35].

Health systems constitute the front line of preparedness, response, and recovery in CBRN accidents. Besides surveillance and early warning, core functions include hospital-level readiness (decontamination corridors, isolation capacity, stockpiles, and safe use of personal protective equipment with heat-stress management), surge capacity and triage, continuity of essential services, and interoperable incident command with public health, EMS, and law-enforcement partners [12,14–15,20]. Continuous training and simulation are pivotal to maintain competencies and coordination across prehospital and hospital teams, with technology-enhanced approaches increasingly used to standardise drills and decision support [13,22–23]. Collectively, these functions position the health system as a critical risk-governance actor that can translate scientific guidance into operational capability during mass-casualty and cross-border CBRN emergencies [10,19]. Each of the study's aims has been addressed through quantitative and network-based analyses, offering an integrated understanding of how CBRN research has evolved over time and across regions.

Taken together, these findings indicate that CBRN research has matured into a multidimensional, globally interconnected scholarly domain. It increasingly integrates technological innovation, cross-sectoral collaboration, and evidence-based policy development to address the complex challenges posed by contemporary CBRN threats [45]. The study underscores the need for future research to maintain agility, foster balanced North–South collaborations, expand thematic coverage into underexplored areas, and enhance the practical applicability of research through stronger engagement with policy and operational frameworks. As global security dynamics continue to evolve, these measures will be pivotal for ensuring that CBRN scholarship remains relevant, inclusive, and impactful.

5. Conclusion

This study presents a comprehensive bibliometric analysis of global Chemical, Biological, Radiological, and Nuclear (CBRN) research from 2010 to mid-2025, integrating temporal, geographical, and conceptual perspectives. Results show a steady growth in CBRN publications, with a significant surge after 2015 and particu CBRN threats, Bibliometric analysis, Global health security, Research trends, Public Health CBRN threats, Bibliometric analysis, Global health security, Research trends, Public Health larly following the COVID-

19 pandemic. The United States and the United Kingdom remain dominant contributors, while increased activity from emerging regions such as Qatar and Malaysia highlights the field's expanding global reach. Thematic mapping revealed four primary clusters—preparedness and training, biosecurity, policy and governance, and technological innovation—underscoring the field's growing interdisciplinarity and practical orientation.

Overall, CBRN research has evolved into a complex, interconnected domain that increasingly merges simulation technologies, artificial intelligence, and governance frameworks. Sustaining this progress will require stronger North–South collaborations, broader open-access knowledge exchange, and closer integration between science, policy, and practice. The study also emphasizes the vital role of health systems in managing CBRN incidents, recommending investments in hospital preparedness assessments, decontamination and isolation capacity, adaptive surge protocols, and interagency simulation exercises supported by decision-support tools. Strengthening these capacities will enhance early detection, reduce secondary contamination, and improve response outcomes during future CBRN events.

6. Recommendations

Based on the findings of this bibliometric analysis, several strategic recommendations are advanced to guide future CBRN research and policy development:

- **Foster interdisciplinary integration:** Future research should bridge technical, policy, and medical domains by integrating emerging tools such as machine learning, simulation modelling, and decision-support systems into emergency preparedness and response.
- **Strengthen South–North collaboration:** Enhancing research partnerships between high-income and underrepresented regions is essential to improve global preparedness, diversify perspectives, and promote equitable capacity building.
- **Promote open-access dissemination:** Expanding open-access publishing and transparent data-sharing practices will facilitate the equitable diffusion of scientific knowledge, particularly in low-resource and developing contexts.
- **Prioritize simulation-based and virtual training:** Greater investment in immersive, scenario-driven, and virtual reality–based training programs can significantly improve operational readiness and interagency coordination.
- **Enhance the science–policy interface:** Establishing structured advisory mechanisms, policy briefs, and knowledge exchange forums can strengthen the translation of research evidence into effective policy and institutional practice.

- **Address thematic and methodological gaps:** Future studies should incorporate longitudinal and mixed-methods designs to advance understanding of long-term risk modelling, psychosocial dimensions, and cross-border coordination mechanisms.

These recommendations underscore the need for an agile, interdisciplinary, and globally inclusive CBRN research ecosystem—one that effectively bridges science, policy, and practice to enhance resilience against evolving CBRN threats.

7. Limitations

This study is bounded by Web of Science and Scopus coverage; domestic repositories, grey literature, and non-English outputs were excluded, and the open-access filter may introduce selection bias. Bibliometric indicators depend on database metadata, with potential errors in author/affiliation disambiguation and country attribution. Network results are sensitive to parameter choices (e.g., thresholds, clustering resolution, counting scheme). Citations are time-dependent and not field-normalised, so recent papers are affected by citation lag. For readability, main-text figures show simplified schematic renderings of the VOSviewer maps; full, unfiltered maps are provided in the Supplementary Material. Finally, the review offers a time-bounded snapshot up to May 2025 and does not appraise the methodological quality of individual studies.

Ethics: This study did not involve human participants/animal subjects; ethical approval was not required.

Competing Interests: The authors have no relevant financial or non-financial interests to disclose.

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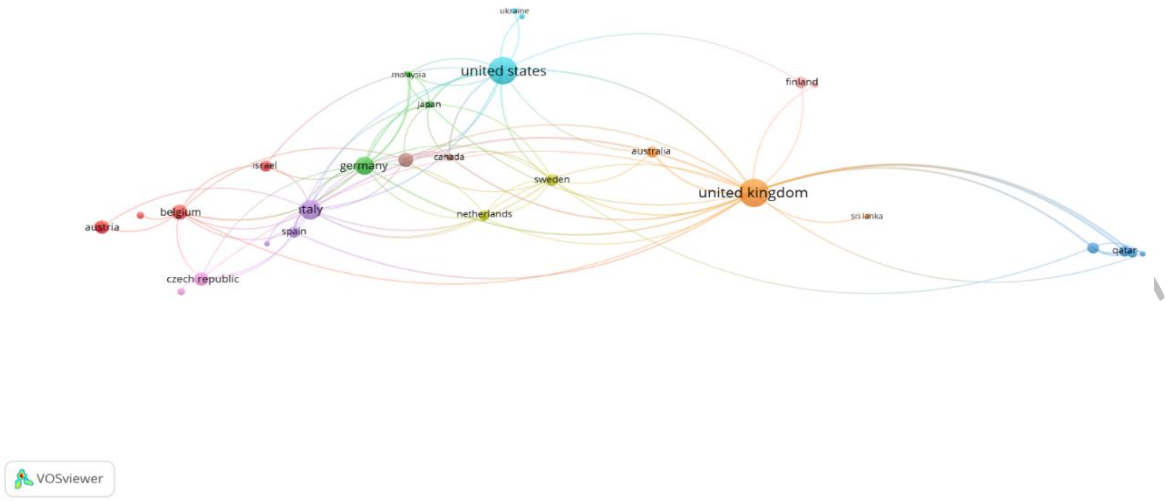
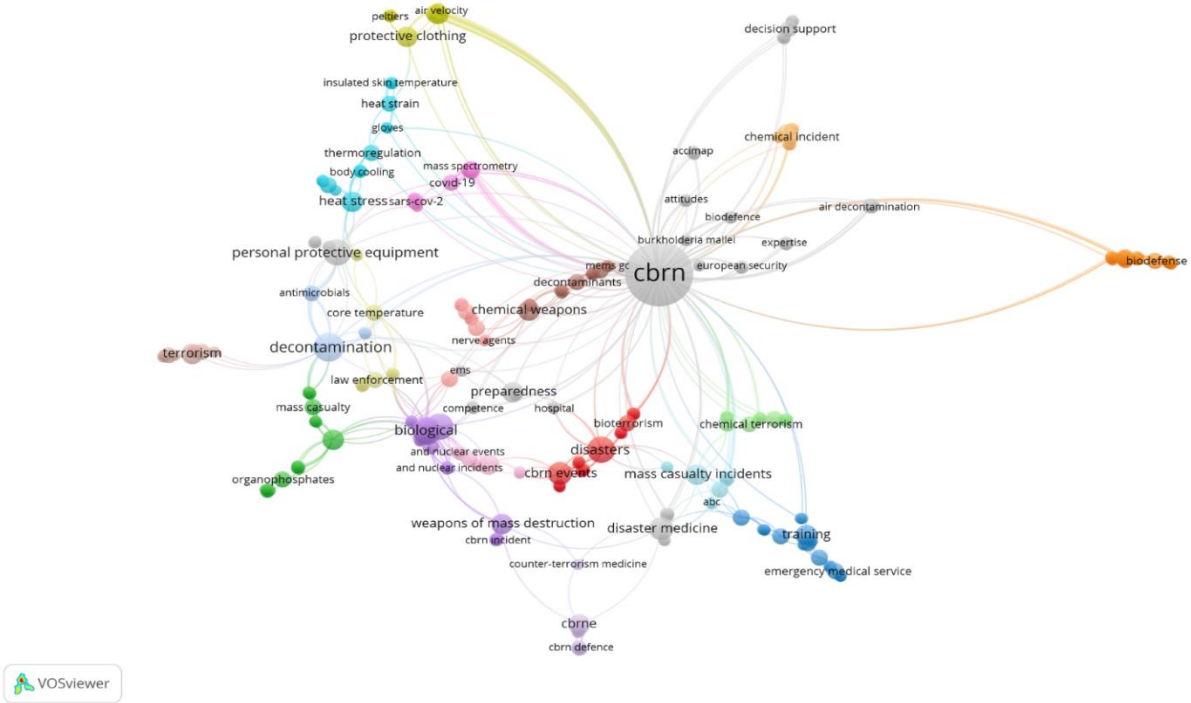
Supplementary



Supplementary Figure S1. Full VOSviewer co-authorship map (countries).



Supplementary Figure S2. Full VOSviewer keyword co-occurrence map.