Mapping Quantitative Methods for Multi-Scale Disaster Resilience: A Bibliometric Review and Research Agenda

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ABSTRACT

This study provides a systematic bibliometric review of quantitative methods for assessing disaster resilience across multiple spatial and organizational scales. Drawing on 909 published in WoS Core Collection from 2003 to 2024, it explores the evolution of methodological frameworks, research hotspots, and cross-disciplinary applications within the field of disaster risk reduction. The findings indicate a clear progression from conceptual discussions of resilience to the development of operational assessment models. Commonly applied approaches include multi-index evaluation methods such as AHP, TOPSIS, and FCE, alongside simulation techniques, probabilistic algorithms, and, more recently, intelligent optimization models. These tools have been utilized to evaluate resilience in infrastructure systems, urban regions, and vulnerable communities. The analysis identifies persistent gaps in international collaboration and highlights a research imbalance between developed and developing regions. Co-occurrence and burst detection analyses reveal that performance measurement, system adaptiveness, and resilience indicators are among the most active research themes. The growing emphasis on preparedness, social equity, and data-driven modeling reflects a broader shift toward dynamic and inclusive frameworks. By mapping knowledge domains and identifying key methodological pathways, this study offers a structured understanding of how disaster resilience is quantitatively assessed and where future research may be directed. The findings provide a reference for scholars, planners, and policymakers seeking scalable, evidence-based strategies to strengthen resilience across diverse risk environments.

Keywords: Disaster Resilience, Quantitative Assessment, Resilience Indicators, Disaster Risk Reduction, Bibliometric Analysis, Multi-scale Systems

INTRODUCTION

In recent years, natural disasters, including floods, earthquakes, hurricanes, tsunamis, landslides, typhoons, heatwaves, droughts, and mudslides, as well as man-made disasters such as fires, environmental pollution, epidemics, and extreme attacks, have occurred frequently across the globe [1]. These disasters have inflicted substantial damage on human society, urban areas, and various systems. There has been a growing interest in quantitative evaluation methods for resilience. These methods primarily encompass but are not limited to resilience measurement based on temporal changes in resilience curves, system modelling through statistical analysis, scenario simulation, and the development of evaluation index systems [2], [3]. Quantitative evaluation methods for resilience constitute valuable tools in disaster risk reduction efforts, and reviewing existing research findings is crucial for the construction of resilient systems at various levels.

Existing reviews have provided valuable insights into the evolution of resilience research from a variety of perspectives, including spatial mapping and disaster contexts [4], conceptual and urban theoretical debates [5], community-based flood resilience frameworks [6], and archaeological-historical analysis of long-term sustainability [7]. Other studies have taken engineering-oriented views, focusing on infrastructure systems [8], critical infrastructure interdependencies and risk management [9]. While these perspectives collectively enrich the field and underscore the multidimensionality of resilience, a notable gap remains: there is a lack of systematic reviews that specifically examine resilience from the perspective of quantitative assessment methods, particularly in the context of disaster risk reduction. Addressing this gap is essential for advancing evidence-based urban resilience planning and governance.

To address this gap, this article summarizes the development process and stage characteristics of quantitative evaluation research for resilience based on bibliometric analysis of visual knowledge graphs. It discusses the application of different quantitative evaluation methods in resilience evaluation within the field of disaster reduction and analyzes possible future trends and priorities. This analysis has important implications for subsequent research and practice.

METHODOLOGY

This article examines the progress of quantitative evaluation methods for resilience in the field of disaster risk reduction in three steps. The initial step involves searching and screening relevant literature in this field using the Web of Science (WoS) Core Collection to gather data. In the second step, WoS Core Collection, Cite Space, and VOSviewer are utilized as tools for quantitative analysis and visual representation of the collected data. The content analyzed and represented encompasses: (1) the overall situation of research development, including the count of articles and the main countries where articles are published; (2) the cooperation network of research institutions; (3) the composition of the knowledge base, and the main concerns in this research field; (4) the phased hot spots and research trends of the research field. The final step summarizes the stages and characteristics of research development, analyzes the application of different quantitative research methods in the field of disaster reduction, understands the development of resilience indicators, and discusses and predicts future development trends.

This article employed Cite Space (version 6.1.R6) and VOSviewer (version 1.6.20) for quantitative analysis and visual representation of the collected data. Both tools are widely used in the field of knowledge graph analysis. Cite Space is a tool designed to visually analyze the structure, patterns, and distribution of scientific knowledge. It is frequently utilized to investigate the development, trends, and hotspots within research fields [10], [11]. VOSviewer, on the other hand, is a software tool for constructing bibliometric networks, adept at generating maps of publications, authors, journals, or keywords based on citations, bibliographic coupling, co-citations, or networks [12], [13].

In this study, Cite Space (version 6.1.R6) was selected as the primary tool for analyzing and visually representing geographical distribution, researchers' distribution, institutional distribution, phased hot spots, and research trends. The Link Strength was set to "cosine," and the Link Scope was set to "within slices." Other parameters were determined based on the specific tasks. VOSviewer (version 1.6.20) was chosen as the tool for analyzing and visually representing the knowledge foundation and main concerns based on co-citations of keywords and references. The parameters for this tool were also determined based on the specific tasks.

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Data Collection

To ensure wide search coverage and high authoritativeness of the retrieved documents, the WoS Core Collection was selected as the document source [14], [15]. To gain a comprehensive understanding of the research development in this field, the earliest search time provided by the WoS Core Collection, which is January 1970, was used as the upper time limit. The lower time limit was set to September 2024.

An advanced search was conducted using the following Boolean operators: TS=("disaster*" OR "flood*" OR "earthquake*" OR "seismic*" OR "accident*" OR "hurricane*" OR "tsunami*" OR "geological disaster*" OR "landslide*" OR "typhoon*" OR "heat*" OR "drought*" OR "fire*" OR "mudslide*" OR "emergencies*" OR "event*") AND TS=("resilience*" OR "toughness*" OR "reliability*" OR "robustness*") AND TS=("assess*" OR "evaluate*" OR "measure*" OR "analysis*" OR "model*") NOT TS=("reliability*" OR "robust*" OR "vulnerability*"). In these operators, TS represented the topic, and * served as a wildcard for fuzzy searching. As a result of the search, a total of 34,176 documents were obtained.

To ensure objectivity and reproducibility in the article selection process, we adopted a two-step screening strategy based on clearly defined inclusion and exclusion criteria. These criteria included thematic relevance to disaster resilience and quantitative methods, original research type, English language, and indexing in the WoS Core Collection. A double coding approach was applied, whereby two authors screened the titles and abstracts of the retrieved articles. The authors discussed and negotiated the parts with differences to determine. This process helped enhance the consistency and reliability of the literature selection. The full selection process is illustrated in the PRISMA flow diagram (Fig. 1).

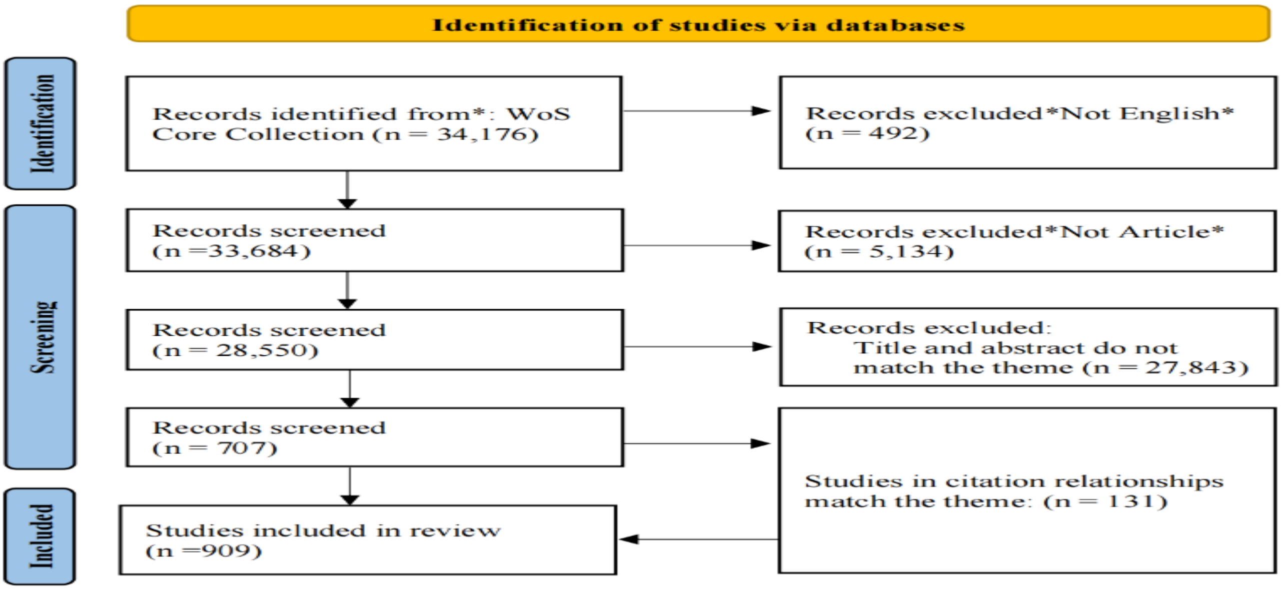

Fig. 1 PRISMA flow diagram

To evaluate inter-rater reliability during the article screening process, Cohen's Kappa coefficient was computed based on a random sample of 200 articles assessed independently by two reviewers. The observed agreement rate was 81.5%, and the calculated Kappa value was 0.617, indicating substantial agreement according to Landis and Koch's benchmark (1977). Discrepancies were discussed and resolved through consensus, ensuring consistent application of the selection criteria across the full dataset.

After screening, 778 articles were retained, and an additional 131 articles that fit the topic were added through citation relationships, bringing the total to 909. The data for these articles can be found in the dataset [16].

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DATA ANALYSIS AND RESULTS

A. Time Distribution

The time distribution of articles can reflect the research heat and development trend of this research field [17], [18]. The annual distribution of 909 articles is shown in Fig. 2. The columns and the numbers above them represent the number of articles published each year, while the curve illustrates the trend of increasing article publication.

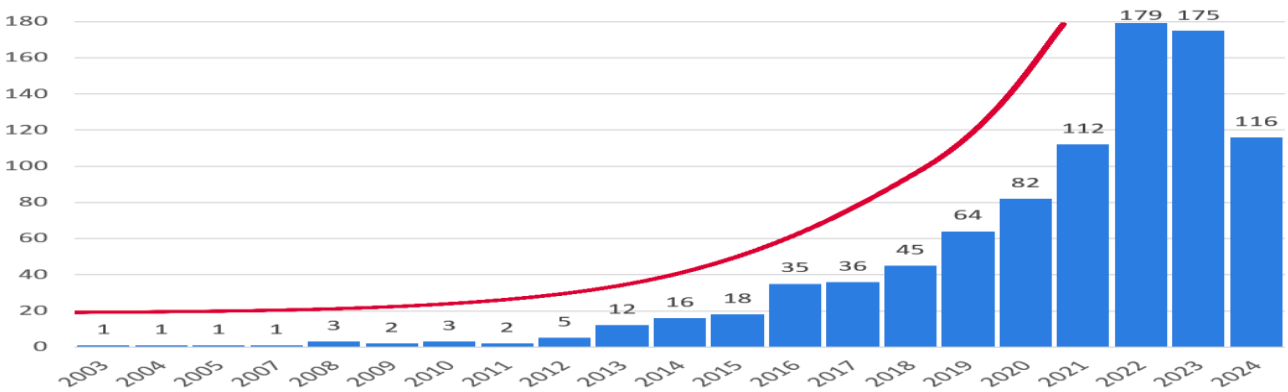

Fig. 2 Time distribution of the articles

From 2003 to 2012, the number of research articles on quantitative resilience evaluation in disaster risk reduction was less than 10 per year. This indicates that the field was in its initial stages and had not yet gained significant popularity. From 2013 to 2018, there was a notable increase in the number of articles, albeit at a slower growth rate. This suggests that research in this field was in the exploratory stage. This phenomenon may be attributed to the frequent occurrence of disasters worldwide and the introduction of the Sendai Framework for Disaster Risk Reduction. Since 2019, the number of articles has experienced rapid growth, demonstrating a sustained and rapid upward trend. This indicates that quantitative resilience evaluation research in the field of disaster risk reduction is gradually evolving into a more established system.

B. Geographical Distribution and Cooperative Relationships

Fig. 3 illustrates the geographical distribution and cooperative relationships of the 909 articles.

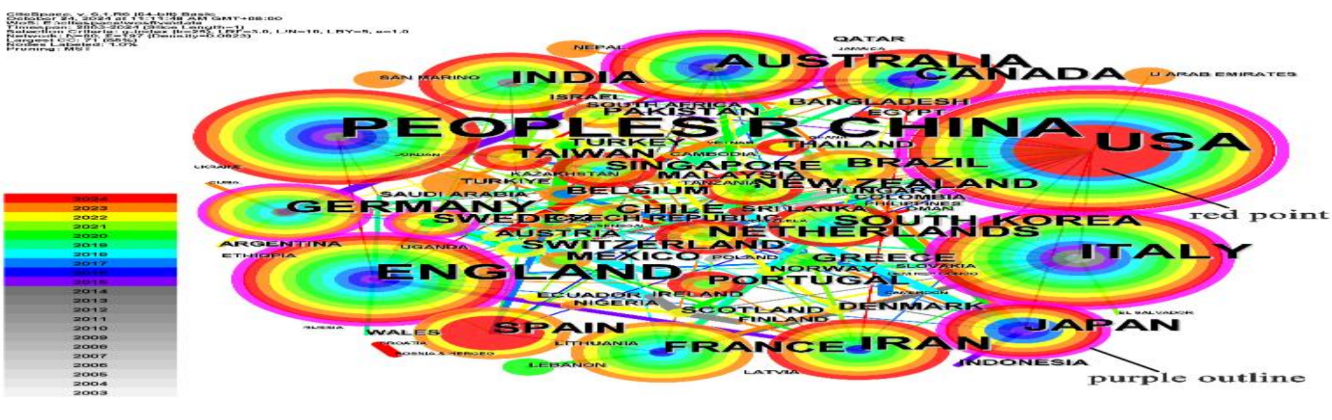

Fig. 3 Geographic distribution and collaborative relationships of the articles

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In the figure, each country's (region's) nodes are represented in the form of historical annual rings. The colors of the rings, from the inside to the outside, correspond to the years in which the papers were published. Consequently, the size of the node is indicative of the duration of research conducted in that country (region), with larger nodes signifying a longer research history. The font size of the country (region) names reflects the citation rate of the articles from that country. Specifically, a larger font size indicates a higher citation rate. The thickness of the links between countries (regions) represents the degree of collaboration between them. Thicker links signify closer cooperation. Additionally, the different colors of the links denote the year of the initial collaboration. The specific year corresponding to each color can be found in the legend located in the bottom left corner of the figure.

A Cite Space analysis of the 909 articles revealed a network comprising 80 nodes and 197 links (Fig. 3). This indicates that the articles originated from 80 countries and that international collaboration occurred 197 times. China contributed the highest number of articles (343), followed by the United States (241). These two countries accounted for 63.25% of the total publications, demonstrating a dominant position in the field.

Table 1 presents the top 10 countries by article count. Notably, seven of these are developed countries. The "centrality" value in the table refers to the level of communication between the country and other countries, which can reflect the importance and influence of the country's articles [19]. Eight countries exhibited a 'centrality' value exceeding 0.1, signifying higher influence. These countries are highlighted with purple outlines in Fig. 3. The United States (0.45), England (0.28), and Italy (0.20) demonstrated the highest 'centrality' values. The United States and Spain are marked with red points in Fig. 3, indicating that the two countries experienced the strongest citation bursts, suggesting a high level of recognition and innovation for research from these two countries.

TABLE 1 TOP 10 COUNTRIES WITH THE MOST PUBLICATIONS

No.	Count	Proportion	Centrality	Begin Year	Country
1	334	36.74%	0.07	2012	PEOPLES R CHINA
2	241	26.51%	0.45	2003	USA
3	76	8.36%	0.28	2013	ENGLAND
4	62	6.82%	0.20	2010	ITALY
5	48	5.28%	0.12	2012	AUSTRALIA
6	44	4.84%	0.06	2013	IRAN
7	32	3.52%	0.06	2004	CANADA
8	31	3.41%	0.06	2014	INDIA
9	29	3.19%	0.13	2014	GERMANY
10	26	2.86%	0.18	2009	JAPAN

Based on these findings, it can be concluded that developed countries have played a significant role in driving and leading research in this field.

C. Distribution of Institutions

To identify the leading publishing institutions and their collaborative relationships over the past 22 years, a slice encompassing 2003 to 2024 was selected, and the top 50 institutions with the highest citation counts were extracted (Fig. 4). An analysis utilizing Cite Space revealed that the institution network consists of 350 nodes and 217 links. This indicates that 350 institutions have published in this field, with 217 instances of collaboration, suggesting a relatively low level of inter-institutional cooperation.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue VII July 2025

In Fig. 4, the size of the nodes corresponds to the number of publications by each institution, while the thickness of the links represents the degree of collaboration. Notably, 26 institutions have a "centrality" value exceeding 0.1, which is highlighted by a purple outline. This suggests that these institutions exert a considerable influence within the research field. The three institutions with the highest "centrality" values are Shandong University (0.58), Delft University of Technology (0.53), and South China University of Technology (0.46).

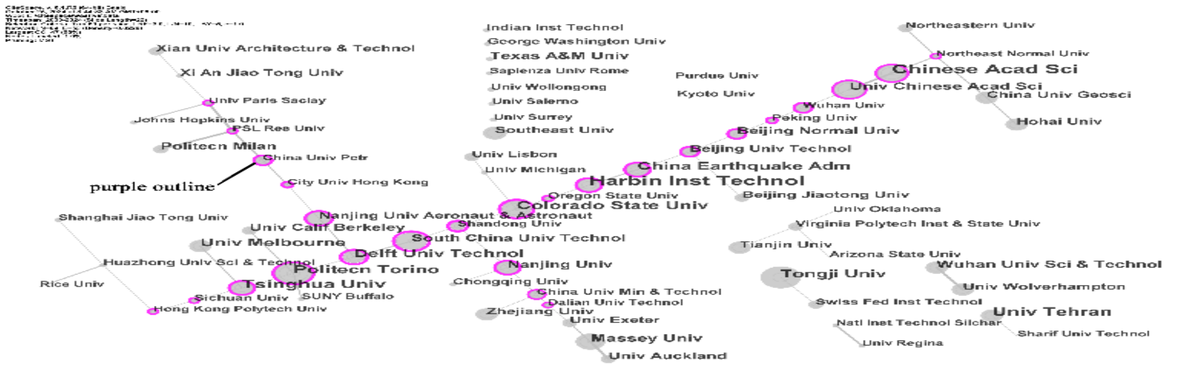

Fig. 4 Institutions and collaborative relationships

The cooperation network depicted in the figure is characterized by straight, single-line connections without cross-connections, highlighting the limitations and weaknesses in inter-institutional collaboration. These findings imply that enhancing cooperation among global institutions may emerge as a future development trend in this field.

Table 2 presents the top 10 institutions by publication volume. The Harbin Institute of Technology (19), Chinese Academy of Sciences (17), and Tsinghua University (14) emerged as the top three. However, the distribution of publications across institutions is relatively dispersed, suggesting a lack of dominant players in the field.

TABLE 2 TOP 10 INSTITUTIONS WITH THE MOST PUBLICATIONS

No.	Count	Proportion	Centrality	Begin Year	Institution
1	19	2.09%	0.36	2017	Harbin Institute of Technology
2	17	1.87%	0.15	2020	Chinese Academy of Sciences
3	14	1.54%	0.22	2016	Tsinghua University
4	14	1.54%	0	2013	University of Tehran
5	13	1.43%	0.45	2018	Colorado State University
6	13	1.43%	0.31	2010	Politecnico di Torino
7	12	1.32%	0.53	2018	Delft University of Technology
8	12	1.32%	0	2014	University of Melbourne
9	11	1.21%	0.34	2019	China Earthquake Administration

D. Knowledge Foundation

To elucidate the knowledge foundation of the field, a co-citation cluster analysis was conducted using VOSviewer [13]. This analysis identified 89 highly cited references (cited at least 20 times) from a corpus of 909 articles, resulting in 35,013 citation relationships. The clusters, visualized in Fig. 5, offer insights into the core research themes.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue VII July 2025

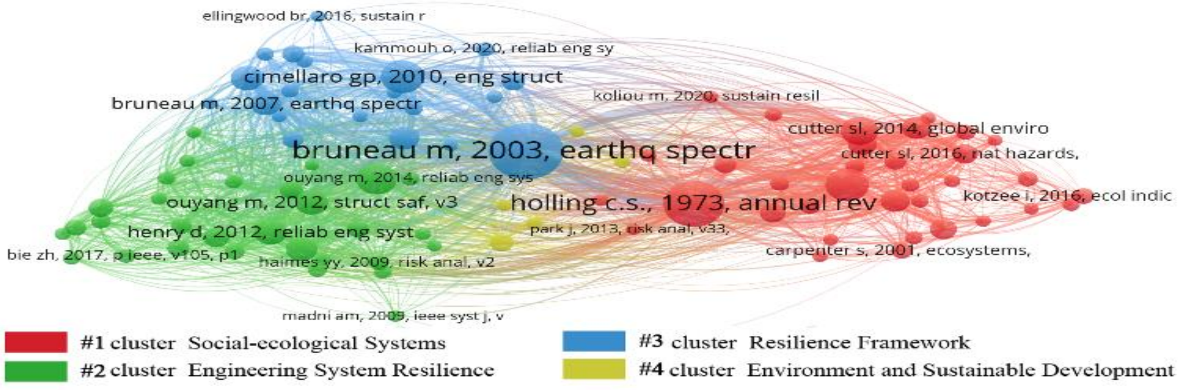

Fig. 5 Co-citation cluster analysis of references

Fig. 5 reveals four distinct clusters. Cluster #1, comprising 34 references, is primarily concerned with social-ecological systems, with Holling and Cutter's work as a key reference. Cluster #2, consisting of 30 references, focuses on engineering system resilience, with Hosseini, Ouyang, Francis, and Henry as influential figures. Cluster #3, with 20 references, is centered around resilience frameworks, with seminal contributions from Bruneau, Cimelaro, and Chang. Finally, Cluster #4, comprising 5 references, emphasizes environmental and sustainable development, with Peet, McDaniels, and Rose as key contributors. These findings indicate that research on the quantitative evaluation of resilience in disaster risk reduction draws upon a multidisciplinary knowledge base, encompassing social-ecological systems, engineering system resilience, resilience frameworks, and environmental sustainability.

Table 3 presents the top 10 most-cited references, highlighting the significant contributions of Bruneau M, Holling CS, Cutter SL, and Cimelaro GP. Holling CS's 1973 introduction of the resilience concept into ecology marked the beginning of its interdisciplinary application. Bruneau M's 2003 resilience triangle method established a foundational framework for quantitative resilience assessment. Building upon these seminal contributions, subsequent research has led to refinements and advancements in methodologies [20]. In 2010, Cimelaro GP proposed a graphical representation of resilience as a function curve to analyze loss and recovery dynamics, while Cutter SL proposed the Baseline Resilience Indicators for Communities (BRIC) based on 6 dimensions (social, economic, housing and infrastructure, institutional, community, and environmental). The pioneering work of these scholars has laid the groundwork for quantitative resilience evaluation and continues to shape the trajectory of this field.

E. Main Concerns

Co-occurrence analysis of keywords can help observe issues of concern in this research field [12], [13]. Use VOSviewer for co-occurrence analysis of all keywords (author keywords and keywords plus). From a total of 3,654 keywords, 105 keywords appearing more than 10 times were selected for analysis, resulting in the clusters visualized in Fig. 6.

Fig. 6 reveals five primary research clusters. Cluster #1, comprising 34 keywords, is primarily concerned with community resilience, vulnerability, and management, highlighting the application of resilience measurement in multidisciplinary studies. Cluster #2, with 25 keywords, focuses on models, performance, and infrastructure, emphasizing internal factors influencing resilience. Cluster #3, consisting of 19 keywords, is centered around resilience frameworks and networks, with keywords such as "resilience," "framework," and "seismic resilience" being prominent. Cluster #4, also with 19 keywords, emphasizes quantitative evaluation methods for resilience, with keywords like "resilience evaluation," "metrics," and "seismic resilience" being central.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue VII July 2025

Finally, Cluster #5, with 8 keywords, highlights external factors influencing resilience, focusing on disasters, hazards, and communities.

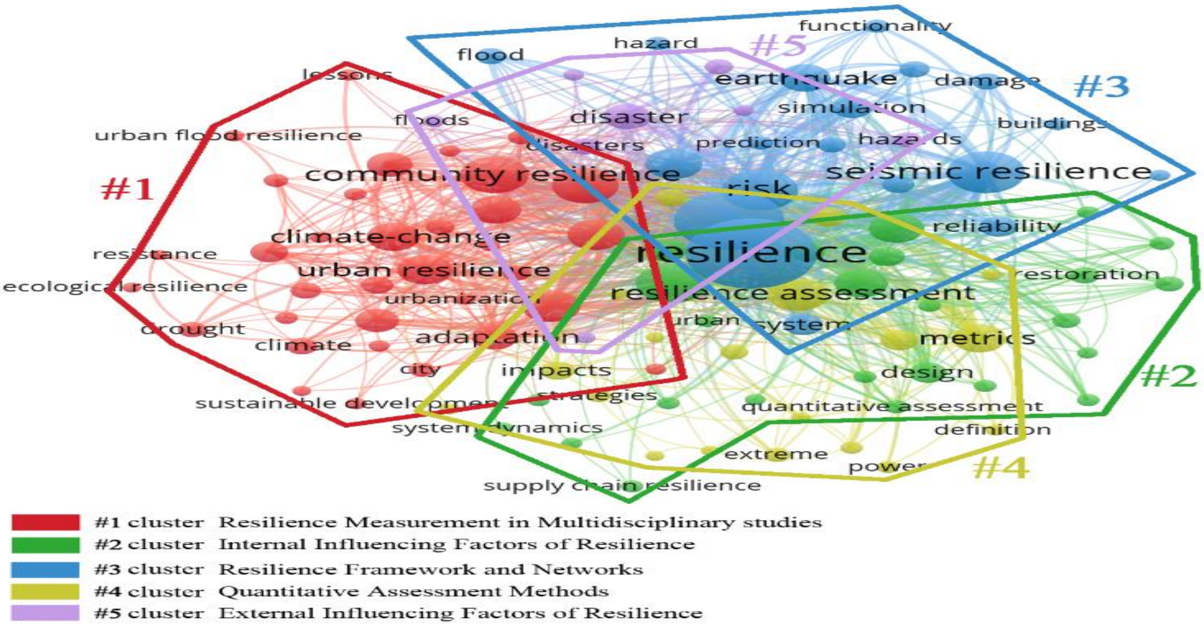

Fig. 6 Co-occurrence cluster analysis of keywords

TABLE 3 TOP 10 MOST CITED REFERENCES

No.	Reference Title	Year	Author	Citations
1	A framework to quantitatively assess and enhance the seismic resilience of communities	2003	Bruneau M	315
2	Resilience and stability of ecological systems	1973	Holling CS	216
3	Temporal and spatial changes in social vulnerability to natural hazards	2008	Cutter SL	125
4	Framework for analytical quantification of disaster resilience	2010	Cimellaro GP	124
5	Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development	2016	Hosseini S	114
6	Disaster resilience indicators for benchmarking baseline conditions	2010	Cutter SL	96
7	A three-stage resilience analysis framework for urban infrastructure systems	2012	Ouyang M	78
8	Generic metrics and quantitative approaches for system resilience as a function of time	2012	Henry D	77
9	Seismic resilience of a hospital system	2010	Cimellaro GP	75
10	A metric and frameworks for resilience analysis of engineered and infrastructure systems	2014	Francis R	71

Co-occurrence density analysis of keywords serves as a valuable tool for promptly identifying significant domains within the graphical representation (as depicted in Fig. 7) [12], [13]. This visual map employs a color gradient of red, yellow, and blue to denote varying densities, with red representing the highest density and blue the lowest.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue VII July 2025

Upon examination of Fig. 7, it is evident that cluster #3 demonstrates the highest keyword co-occurrence density, with the densest regions rendered in yellow. This finding implies that current research endeavors are concentrated on resilient frameworks and networks, although there remains substantial scope for enhancing the breadth and depth of research interests in this area.

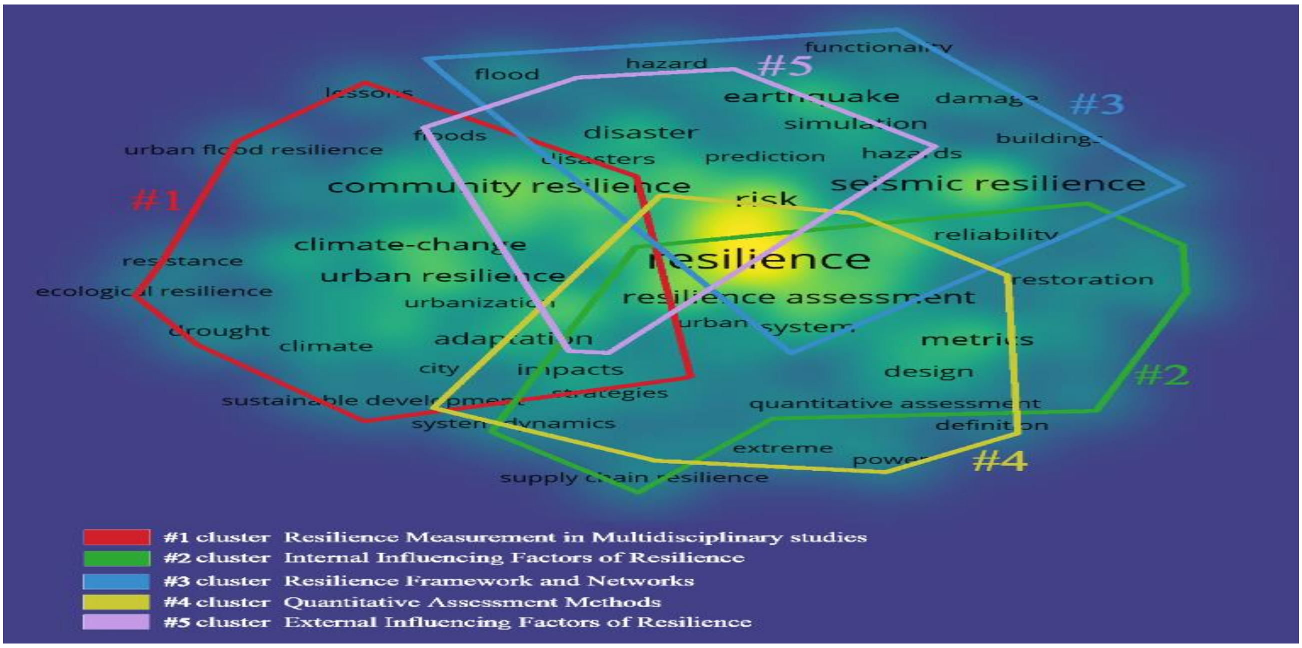

Fig. 7 Co-occurrence density analysis of keywords

F. Phased Hot Spots and Research Trends

Keyword burst detection serves as an effective means of identifying phased hot spots within a research domain [21]. By utilizing the keyword burst detection function in CiteSpace, a total of 8 burst keywords were identified, leading to the generation of Fig. 8. The analyzed time span covers the period from 2019 to the present.

In Fig. 8, the red line signifies the duration of each keyword burst. Notably, the keyword "strategy" emerged in 2013 and subsequently became a prominent topic of discussion from 2019 to 2022, exhibiting the longest burst duration. This suggests that the research field extensively debated strategies related to resilience during this timeframe. Furthermore, "resilience evaluation" displayed the strongest citation burst and remains an ongoing hot topic. Additionally, "optimization," "performance," and "resilience evaluation" have gained significant attention since 2022 and continue to experience a surge in research interest, indicating that internal factors influencing resilience evaluation are gradually becoming focal points of investigation in this field.

Fig. 8 Keywords with the strongest citation bursts

Identifying references with the strongest citation bursts can aid in pinpointing the research frontier [21]. Using CiteSpace, 52 references with notable citation bursts were detected. The highest strength value was attributed to Hosseini S's article, "A review of definitions and measures of system resilience," published in Reliability Engineering & System Safety in 2016. This review article delves into the definition and quantification methods of system resilience within the engineering systems field, employing a classification scheme to distinguish between qualitative and quantitative approaches. The citation burst of this article underscores the heightened research interest in resilience measures that occurred from 2018 to 2021. CiteSpace shows that citations of nine articles by Sun WJ (2020), Liu W (2020), Kammouh O (2020), Bertilsson L (2019), Zinetullina A (2021), Chen CK (2021), Poulin C (2021), Zhou YM (2019), and Sharma N (2020) have continued to exhibit bursts. The persistent citation bursts of these articles suggest that future quantitative research on resilience holds significant development potential in the fields of engineering and urban studies. Moreover, the high-frequency occurrence of theme words such as "infrastructure," "dynamic Bayesian network," and "metrics" in these articles indicates that metrics evaluation in various systems is likely to emerge as a prominent research trend in future resilience quantitative research.

DISCUSSION

Upon gaining a comprehensive understanding of the development trajectory of this research field, the ensuing discussion is conducted.

A. The Stages and Characteristics of the Research Development

Research on resilience quantitative evaluation within the disaster risk reduction field has undergone three distinct stages, as evidenced by the number of literature publications. These stages include the initial stage (2003-2012), the exploratory stage (2013-2018), and the rapid development stage (since 2019).

In the initial stage of development, only 19 studies had been published, most of which examined how systems perform during the loss phase of resilience in response to isolated disaster events. At that time, the concept of resilience in disaster risk contexts was still evolving—frequently discussed through adjacent terms like vulnerability, robustness, or reliability [22]-[24]. The classification of resilience stages was also in flux but began to take clearer shape toward the end of this period. A typical division during this stage included three basic phases: the initial state, the disruption or loss phase, and the recovery. Scholarly attention was largely directed toward the latter two, with the idea of “resilience loss” shifting from a momentary shock to an extended process. Recovery was generally assumed to restore the system to its original state [25] - [28]. Among these early contributions, Bruneau M.’s 2003 paper stands out as a formative milestone. It not only helped sharpen the conceptual boundaries of resilience but also introduced a quantitative framework that has since been widely cited and adapted across contexts [20], [29], [30].

Between 2013 and 2018, the literature began to refine both conceptual and structural understandings of resilience. While taxonomies varied slightly across studies, most proposed models organized the resilience process into three to six stages, commonly including elements like preparation, resistance, absorption, adaptation, and recovery. Despite this diversity, emphasis remained centered on the disruption and recovery phases, where efforts to operationalize and enhance resilience were most evident [6], [31] - [37].

Since 2019, research activity has grown rapidly, with 728 publications emerging in less than six years. This surge has coincided with greater consensus around a four-stage resilience cycle: prevention (or preparation), withstand (encompassing resistance or absorption), recovery (bounce-back), and adaptation (transformation). Much of the recent literature now focuses on identifying effective interventions at each phase, with growing recognition that a system's final post-event state may not necessarily return to baseline, but could instead fall below or rise above its original condition, depending on contextual factors and intervention strategies [38] - [46].

In summary, four characteristics have been identified through observing the cognition of resilience in literature across different eras:

1. Recognition Shift: the recognition of resilience status has changed from static to dynamic.
2. Stage Division Evolution: the division of resilience stages has changed from chaos to approaching unity.
3. Goal Transformation: the ultimate goal of resilience is to go from returning to the single original level to acknowledging the coexistence of multiple possibilities and applying human intervention to achieve the purpose of enhancing resilience.
4. Focus Expansion: from looking for ways to enhance resilience only in the recovery stage to taking different measures to enhance resilience in different stages.

B. Application of Quantitative Methods

To gain insight into the application of various quantitative evaluation methods in the field of disaster risk reduction, this study conducted a comprehensive analysis of 909 articles. Specifically, we counted the frequency of occurrence, application methods, and primary data collection techniques employed by different quantitative evaluation methods. The top five quantitative research methods with the highest application rates are presented in Table 4. As depicted in Table 4, the three most frequently used methods are the evaluation model, the multi-index evaluation method, and simulation. The evaluation model is commonly applied in research areas such as Environmental Sciences, Civil Engineering, and Water Resources. The multi-index evaluation method is more prevalent in fields like Environmental Sciences, Water Resources, and Geosciences Multidisciplinary. Simulation, on the other hand, is primarily utilized in Civil Engineering, Energy Fuels, and Electrical and Electronic Engineering.

It is worth noting that many articles employ more than one method. For instance, over half of the articles that use the multi-index evaluation method also incorporate an evaluation model. Among the articles utilizing the simulation method, 27 also employ a probabilistic algorithm, and 18 are combined with an optimization algorithm, among others.

As illustrated in Fig. 9, an analysis of the annual frequency of various methods reveals notable trends. Specifically, the application of evaluation models and multi-index evaluation methods has continued to exhibit a rapid growth trajectory. Conversely, the growth rate of simulation has been relatively modest. While the use of probabilistic algorithms and optimization models has shown an overall increase, there are discernible fluctuations in their application. According to the literature, probabilistic algorithms and optimization models are primarily concentrated in research domains related to engineering technology and intelligent engineering.

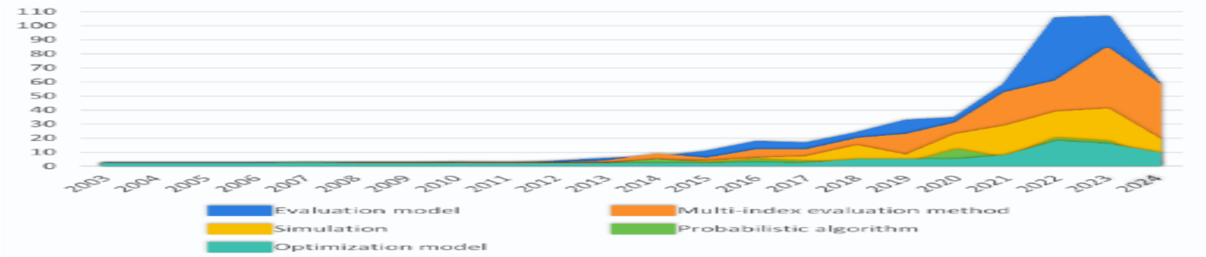

Fig. 9 Yearly quantity chart of top 5 quantitative evaluation methods

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These observations suggest that the application of evaluation models and multi-index evaluation methods in the quantitative evaluation of resilience for disaster risk reduction is maturing and experiencing swift development. This may be attributed to their adaptability to interdisciplinary integration. Simulation, on the other hand, is demonstrating steady progress in fields such as civil engineering, energy fuels, and electrical and electronic engineering. The probabilistic algorithm and optimization model have secured a niche in research areas including civil engineering, industrial engineering, and green sustainable science and technology. With advancements in technology and the growing demand for intelligence, these methods have the potential to make significant strides in the future.

In addition, several novel methods have been introduced in the quantitative evaluation of resilience for disaster risk reduction in recent years. Specifically, the application of load modeling in microgrid resilience evaluation was introduced in 2017 (with 13 articles), the application of the cloud model in resilience evaluation in geosciences multidisciplinary and meteorology atmospheric sciences (with 11 articles) was introduced in 2019, the application of Recurrent Neural Network (RNN) in resilience evaluation in infrastructure and urban studies was introduced in 2020 (with 5 articles), among others. These innovative methods have not only expanded the research horizons but also injected new vitality into the field of resilience quantitative evaluation for disaster risk reduction. They offer fresh perspectives and approaches for future research endeavors.

TABLE 4 TOP 5 QUANTITATIVE METHODS FOR DISASTER RESILIENCE ASSESSMENT (2003–2024)

Methods	Size	Application	Data Collection
Evaluation model	479	Resilience is evaluated directly or after improvement using existing evaluation models, often combined with a multi-index evaluation method. Evaluation models include the Analytical Hierarchy Process (AHP), Fuzzy Comprehensive Evaluation (FCE), Grey Relational Analysis (GRA), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Structural Equation Model (SEM), Pressure-State-Response (PSR) Model, etc.	Literature, questionnaires, interviews, observations, etc.
Multi-index evaluation method	374	Analyze the factors that affect elasticity, select indicators, allocate weights, and establish an indicator system to evaluate elasticity strength. Common weighting methods include the Delphi method, Entropy Weight Method (EWM), Analytic Hierarchy Process (AHP), game theory, etc.	Literature, questionnaires, interviews, observations, diary documents, etc.
Simulation	190	Simulate disaster failure scenarios or performance during and after a disaster, determine threshold ranges, and achieve the purpose of predicting the extent of damage or avoiding risks, including Monte Carlo simulation, Bayesian networks, system dynamics (SD), etc.	Literature, observations, log documents, databases, big data, etc.
Probabilistic algorithm	72	To cope with the complexity and uncertainty of the system, iterative updates are required to obtain the optimal solution, including dynamic	Observations, log documents,

		Bayesian network, Monte Carlo analysis, Markov process, etc.	databases, big data, etc.
Optimization model	64	It imitates the laws of nature, calculates the achievable toughness value under the set constraints, and searches for the global optimal solution through iteration, including linear optimization models, genetic algorithms, particle swarm optimization algorithms, back propagation networks, random forest models, etc., and is often used in conjunction with probabilistic algorithms and indicator methods.	Literature, databases, etc.

C. Development of Resilience Indicators

As mentioned earlier, the high-frequency theme words "infrastructure," "dynamic Bayesian network," and "metrics" indicate that the multi-index evaluation method is likely to remain a dominant research approach in this domain. This method typically combines resilience characteristics, components, or influencing factors of the system to propose multiple specific measurement indicators [47], [48]. Alternatively, it may delineate horizontal thresholds for these indicators, or weight and calculate them, to determine the system's resilience level [49], [50]. This approach is considered one of the most intuitive methods for characterizing resilience [51], [52].

Numerous studies on resilience measurement have proposed various indicators. Cai H et al. conducted a comprehensive review of 101 articles that proposed resilience indicator systems between 2005 and 2017 [53]. They categorized the indicators used in these articles into seven distinct categories and identified 16 resilience indicators that were mentioned more than 20 times, as presented in Table 5. Cai's statistical analysis provides valuable insights into the progression of resilience index research up to 2017.

To gain the development of quantitative resilience evaluation indicators from January 2003 to September 2024, this study examined 374 articles that employed the multi-index evaluation method out of a total of 909 articles. A total of 1357 non-repeating indicators were proposed in these articles. To facilitate the analysis of the development trends, these indicators are counted according to the 7 categories provided by Cai H et al. In the meantime, 38 indicators that appeared more than 20 times are listed in Table 6.

As depicted in Table 6, when compared with Table 5, employment, education, income, age, previous disaster experience, and communication capacity continue to be regarded as highly important indicators. However, a notable difference is that researchers have introduced more extensive and in-depth requirements for pre-disaster preparations. These requirements aim to mitigate the impact of disasters and facilitate rapid recovery through various pre-disaster measures. Indicators such as "emergency response plan," "specialization," "early warning," "publicity," and "legalization" reflect this shift in focus.

Another indicator worth mentioning is "vulnerable groups," whose frequency of occurrence has surged in recent years. This trend highlights the increased importance of considering vulnerable groups in disaster research. It is likely that this topic will become a research hotspot in the future. However, a search of the WoS Core Collection using the topic terms "vulnerable groups" and "disaster" yielded only 1,605 English articles as of September 2024. This finding suggests that while researchers have paid attention to the circumstances of vulnerable groups during disasters, specific research addressing these groups has not yet reached a significant scale, leaving ample room for further investigation.

TABLE 5 MOST FREQUENTLY USED RESILIENCE INDICATORS IN RANK ORDER FROM 2005 TO 2017. [53]

Category	Most frequently used indicators	Specific indicator example	Time used
Economic	Income	Median household income	49
Economic	Employment	% labor force employed	44
Social	Educate	% over 25 years old no schooling completed	43
Social	Age	% population 65 years and over	41
Institutional	Previous disaster experience	Disaster frequency	38
Infrastructure	Shelter capacity	Hotels/motels per 10,000 persons	28
Institutional	Social connectivity	% 1-person household	26
Social	Communication capacity	% Households with telephone service available	25
Institutional	Municipal service	% municipal expenditures for fire, police, and EMS	25
Community	Place attachment	% Population born in state of current residence	25
Infrastructure	Transportation access	% Households with at least one vehicle	23
Institutional	Mitigation	% population covered by Citizen Corps programs	23
Economic	Housing capital	% homeownership	22
Infrastructure	Medical capacity	Hospital beds per 10,000 persons	21
Infrastructure	Recovery	Debris removal	21
Community	civic involvement	Civic organizations per 10,000 persons	21

TABLE 6 MOST FREQUENTLY USED RESILIENCE INDICATORS IN RANK ORDER FROM 2003 TO 2024

Category	Most frequently used indicators	Specific indicator example	Time used
Economic	Employment	% labor force employed	71
Social	Education	% over 25 years old no schooling completed	68
Economic	Income	Per capita disposable income	68
Social	Population	Population density	64
Economic	Financial	Per capita GDP	63
Social	Previous disaster	Acquisition of local disaster knowledge	57

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	experience		
Social	Age	% Population aged between 18 and 65	57
Social	Vulnerable groups	% Poor and disabled people with special needs	53
Environmental	Climate	Precipitation	43
Institutional	Cooperation	Cross-departmental collaboration efficiency	42
Infrastructure	Equipment	Outage duration	39
Infrastructure	Communication capacity	Percentage of people covered by mobile Internet	39
Infrastructure	Medical capacity	Number of hospital beds per 10,000 people	39
Economic	Insurance	% Medical insurance coverage	36
Environmental	Ecology	Green coverage rate	36
Institutional	Prepare	Completeness of emergency response plan	36
Institutional	Specialization	% Professionals (fire, police, and EMS)	35
Institutional	Command ability	% Management Personnel	33
Infrastructure	Shelter capacity	Shelter area per capita	32
Others	Recovery	Recovery time	32
Infrastructure	Transportation	Road density	32
Institutional	Risk reduction plan	Government disaster reduction plans and the extent of local disaster response	31
Infrastructure	Early Warning	% Pre-disaster warning coverage	30
Institutional	Publicity	% Disaster reduction publicity and training coverage	29
Community	Place attachment	% Population born in state of current residence	28
Infrastructure	Sewage	% Centralized sewage treatment	28
Infrastructure	Pipeline Network	Drainage pipe density	27
Community	Volunteer	% Volunteer	27
Institutional	Land use	% Land Type	27
Community	civic involvement	Civic organizations per 10,000 persons	27
Environmental	Disaster scope	% Population affected by disasters	24
Infrastructure	Waste	% Harmless treatment of waste	24
Economic	Budget	Government budget for disaster risk reduction	23
Economic	Economic Structure	% Tertiary industry in GDP	23
Social	Urbanization level	Urbanization rate	22
Environmental	Rainwater storage	Water permeability	21

	capacity		
Economic	Loss	Economic losses caused by disasters	20
Institutional	Legalization	Disaster reduction-oriented laws, regulations, and systems	20

CONCLUSIONS

This study presents a knowledge graph visual bibliometric analysis of 909 articles published from January 2003 to September 2024, focusing on resilience quantitative evaluation methods based on disaster risk reduction. The analysis was conducted using WoS Core Collection, CiteSpace, and VOSviewer, which are scientific graph analysis software tools. The study was grounded in the WoS Core Collection core database.

The article elucidates the time distribution of this research, as well as the distribution and collaboration relationships among countries, institutions, journals, and authors. Furthermore, it examines the disciplinary knowledge foundation and main concerns within this field. By further analyzing the bursts of keywords and reference citations, the phased hot spots and research trends were identified, and the future research trend was predicted. Through a comprehensive discussion, the historical development of this research field was summarized, and potential future trends were explored. This analysis provides valuable insights into the evolution, current state, and future trends of resilience quantitative evaluation methods in the context of disaster risk reduction.

Overall, the conclusions are as follows:

1. Research on quantitative resilience evaluation in disaster risk reduction has progressed through three distinct stages: the initial stage (2003-2012), the exploratory stage (2013-2018), and the rapid development stage (since 2019). The development of this field exhibits four notable characteristics: a shift from static to dynamic approaches, a transition from chaos to unity, a change from pursuing a single ultimate goal level to acknowledging multiple possibilities, and a move from solely focusing on enhancing resilience in the recovery stage to implementing different measures at various stages.
2. Although developing countries have contributed to research in this field, the primary drivers and leaders have been developed countries. Journals, authors, and institutions involved in this research are relatively dispersed, indicating a need for stronger research team development and institutional collaboration.
3. The research on resilience quantitative evaluation methods based on disaster risk reduction is grounded in the knowledge foundations of social-ecological systems, engineering system resilience, resilience frameworks, and environment and sustainable development. Current research efforts are concentrated more on resilience frameworks and networks. Internal factors affecting resilience evaluation are gradually emerging as research hotspots. Engineering and urban research hold greater development prospects in this domain. Future research is expected to pay increased attention to pre-disaster preparation and vulnerable groups.
4. In the application of quantitative methods for the quantitative evaluation of disaster risk reduction resilience, the use of evaluation models and multi-index evaluation methods has become increasingly mature and is rapidly developing. The multi-index evaluation method is likely to remain the primary research approach in the future. The simulation method is steadily advancing, while probabilistic algorithms and optimization models have gained significant prominence. The continuous introduction of novel quantitative research methods has sustained the growth and activity of this field, and the future development trend appears optimistic.

Based on the bibliometric analysis and discussion of resilience quantitative evaluation methods in the context of disaster risk reduction, this article presents valuable insights for future researchers in identifying research ideas and directions. However, it should be noted that the data collection for this study was limited to English literature sourced from the WoS Core Collection, which may introduce bias. To address this limitation, future studies could consider incorporating literature data from multiple databases and in various languages for a more comprehensive bibliometric analysis.

Future research should focus on developing integrated assessment frameworks that blend quantitative models with qualitative inputs, particularly in data-scarce or uncertain environments. Cross-scale approaches linking community-level indicators to regional and national metrics are needed to support multi-level policy alignment. While advanced methods such as probabilistic algorithms and optimization models are gaining attention, their integration with real-time data sources—such as satellite imagery, sensor networks, and early warning systems—remains limited. Future work should also expand the geographic scope of resilience studies by involving researchers from underrepresented regions, especially in developing countries. Greater institutional collaboration would enhance the contextual relevance and applicability of resilience assessments. These efforts are essential to advancing more adaptive, inclusive, and evidence-based strategies for disaster risk reduction in an increasingly complex and uncertain world.

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