ISSN 2616-5775 Vol. 7, Issue 10: 105-118, DOI: 10.25236/AJCIS.2024.071015

A Bibliometric Review of Research on the Robustness of Interdependent Networks

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Abstract: *The robustness of interdependent networks is critical to the stability of vital infrastructures, including power grids, transportation, and communication systems, all of which underpin global security, economic continuity, and societal resilience. Increasing disruptions caused by natural disasters, cyberattacks, and systemic risks underscore the need for research into enhancing the robustness of these networks. This paper presents a bibliometric analysis of 4,627 publications from 2007 to 2023, conducted using CiteSpace software to uncover key trends, influential studies, and emerging research areas in the field of interdependent network robustness. The analysis examines publication trends, core authors, leading research institutions, core journals, and highly cited papers, highlighting significant advancements in theoretical models, empirical findings, and applications for improving network resilience. Moreover, keyword co-occurrence, clustering, and burst detection analyses reveal new research directions, such as the study of cascading failures and the integration of artificial intelligence in enhancing network robustness. These findings provide a roadmap for future research, offering valuable insights for addressing the challenges of ensuring the robustness of increasingly complex and interdependent systems.*

Keywords: *Interdependent Networks, Network Robustness, Bibliometric Analysis, Visual Analysis*

1. Introduction

Amidst globalization and rapid technological advancements, complex systems now constitute essential components across various sectors of modern society[1]. These systems typically comprise multiple interdependent networks, including power grids[2], communication systems[3], and transportation networks[4], among others. The interdependencies among these networks imply that failures in one can propagate through connected dependencies, causing cascading effects that may ultimately result in systemic collapse[5]. The potential for such chain reactions highlights the critical importance of studying the robustness of interdependent networks. In particular, within critical infrastructure sectors such as power, transportation, and finance, the robustness of interdependent networks is vital for ensuring societal safety and stability. The growing frequency of global climate change, natural disasters, and cyberattacks has starkly exposed the vulnerabilities of these systems[6]. For instance, the 2012 massive power outage in India[7], which affected approximately 600 million people, underscored the risks inherent in the interdependencies between power networks and other infrastructure systems. Consequently, enhancing the robustness of interdependent networks has emerged not only as a prominent focus in theoretical research but also as an urgent challenge in practical applications.

In recent years, significant advances have been made in the study of network robustness within interdependent systems. Researchers have utilized theoretical modeling[8], computational simulations[9], and empirical analyses[10] to uncover the vulnerabilities and robustness characteristics of complex systems. However, as research advances, discussions surrounding network robustness have grown increasingly intricate. Variations in network models, assumptions, and analytical methods across disciplines have introduced considerable diversity and uncertainty into this research domain. Additionally, the rapid development of big data technologies[11] and complex systems theories[12] has accelerated the pace and complexity of knowledge expansion in this field. Given this context, a systematic review and bibliometric analysis of existing research is essential to elucidate the current state and emerging trends in this field. This study utilizes CiteSpace software to perform a bibliometric analysis of 4,627 articles on interdependent network robustness, published between 2007 and 2023 and indexed in the Web of Science database. The objective is to quantitatively identify key trends, core issues, and major challenges within the field. This study provides not only a detailed review of existing research but also a clear roadmap for newcomers, facilitating their understanding of the complexity and significance of interdependent network robustness. Furthermore, this paper represents the first systematic bibliometric analysis of interdependent network robustness from a bibliometric standpoint. This research enables readers to gain a comprehensive understanding of the developmental trajectory and potential future directions in interdependent network robustness studies, thereby laying a foundation for further theoretical exploration and practical applications.

The remainder of this paper is organized as follows: Section 2 describes the research methods and data sources; Section 3 provides a quantitative analysis of publication numbers, authors, research institutions, journals, and highly cited papers on interdependent network robustness, complemented by visual analysis using CiteSpace; Section 4 reveals research directions and hotspots in network robustness through keyword co-occurrence networks, keyword clustering, and burst analysis; and finally, Section 5 concludes the study.

2. Research Methods and Data Sources

2.1. Research Methods

This study employs a bibliometric approach to systematically analyze research trends in the field of interdependent network robustness[13]. Bibliometric analysis quantitatively evaluates scientific literature, providing insights into key trends, influential authors, and emerging research areas. The analysis was conducted using CiteSpace 6.1.R6 (available at http://cluster.cis.drexel.edu/~cchen/citespace/), a software tool that facilitates the visualization of co-citation networks, keyword co-occurrence, and citation bursts[14]. These features allowed us to identify critical developments, research clusters, and emerging trends within the field, offering a comprehensive overview of the research landscape and guiding future investigations[15].

2.2. Data Sources

To ensure a comprehensive review of the literature on the robustness of interdependent networks, a search was conducted in the Web of Science Core Collection database[16,17]. The keywords for this search included various terminologies related to interdependent networks and robustness[18], specifically: "interdependent networks," "coupled networks," "dependency networks," "multi-layer networks," "multilayer networks," "interconnected networks," "interactive networks," and "interlinked networks," combined with terms such as "robustness," "resilience," "stability," "vulnerability," and "resistance." The search string used was: TS= ("interdependen* network*" OR "coupled network*" OR "dependency network*" OR "multi-layer network*" OR "multilayer network*" OR "interconnect* network*" OR "interact* network*" OR "interlink* network*") AND TS= (robust* OR resilien* OR stabilit* OR vulnerab* OR resist*).

The search covered articles published between 2007 and 2023 and was restricted to those written in English. The following filters were applied: Document Type (Article), Research Areas (Biochemistry Molecular Biology, Science Technology Other Topics, Physics, Engineering, Computer Science, Chemistry, Materials Science, Environmental Sciences Ecology, Mathematics, Biotechnology Applied Microbiology, Mathematical Computational Biology, Genetics Heredity, Automation Control Systems, Telecommunications, Operations Research Management Science, Energy Fuels, Infectious Diseases, Transportation and Business Economics). This search strategy yielded a total of 4,627 articles, capturing a broad range of relevant studies across multiple disciplines, and ensuring the inclusion of diverse perspectives on the robustness of interdependent networks.

3. Quantitative Analysis and Trends

3.1. Annual Growth of Number of Journal Papers

When assessing scientific research output, quality, and contribution to the literature, the number of journal publications is a key indicator[19,20]. The evolution in the number of published papers directly reflects the expansion of knowledge within a specific field. From 2007 to 2023, research in the robustness of interdependent networks has experienced significant growth (Fig. 1). The cumulative number of journal papers in this area follows the fitted curve equation Y=18.65183x1.94303(R^2=0.99, $p<0.0001$),

ISSN 2616-5775 Vol. 7, Issue 10: 105-118, DOI: 10.25236/AJCIS.2024.071015

indicating a strong correlation between time (in years) and the cumulative number of publications[21,22]. This pattern suggests that growth in this area is non-linear and accelerates over time, especially during certain periods. The high coefficient of determination (R^2=0.99) and statistical significance ($p<0.0001$) demonstrate that the model provides an almost perfect fit to the data.

Upon examining the data, we can distinguish three distinct phases of growth: the early steady growth phase (2007–2011), the rapid expansion phase (2012–2020), and the stabilization phase (2021–2023) (Fig. 2).

1) Early Steady Growth Phase (2007–2011):

During this initial five-year period, the number of journal publications increased steadily from 75 in 2007 to 130 in 2011, with an average annual growth rate of approximately 14.6%. The cumulative number of papers rose from 75 to 484 during this time. This phase reflects the gradual emergence of interest in the field, driven by foundational research into complex systems such as power grids and communication networks[23-27]. The early growth aligns with increasing awareness of system vulnerabilities, particularly following events like the 2003 Northeast blackout[28] and the 2007–2008 global financial crisis[29,30], which highlighted the importance of interdependencies in critical infrastructures.

2) Rapid Expansion Phase (2012–2020):

The field experienced a surge in scholarly output during this phase. In 2012, 188 journal papers were published, marking a 44.6% increase from the previous year. The number of annual publications continued to rise sharply, reaching a peak of 443 papers in 2020. Cumulatively, the number of publications grew from 672 in 2012 to 3117 by 2020. The average annual growth rate during this period was around 16.3%, reflecting the growing academic interest in the robustness of interdependent networks, fueled by advancements in modeling[31,32], simulation[33,34], and empirical studies[35,36].

3) Stabilization Phase (2021–2023):

Over the past three years, the number of annual publications has stabilized at approximately 500 papers per year. In 2021, 497 papers were published, followed by 507 in 2022 and 505 in 2023. Although the cumulative number of publications continued to increase, reaching 4,627 by 2023, the annual growth rate has plateaued. This stabilization reflects a saturation of research activity or a shift toward interdisciplinary[37-39] and applied approaches[40-42], particularly in response to global disruptions such as the COVID-19 pandemic, which exposed weaknesses in global supply chains and healthcare networks, further driving the need for resilient systems[43-45].

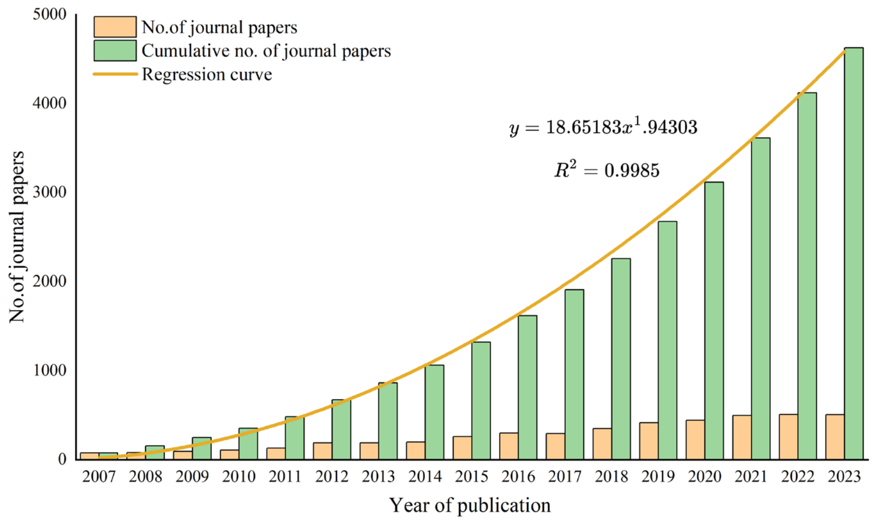

Figure 1: Annual growth of journal papers on interdependent network robustness (2007-2023).

ISSN 2616-5775 Vol. 7, Issue 10: 105-118, DOI: 10.25236/AJCIS.2024.071015

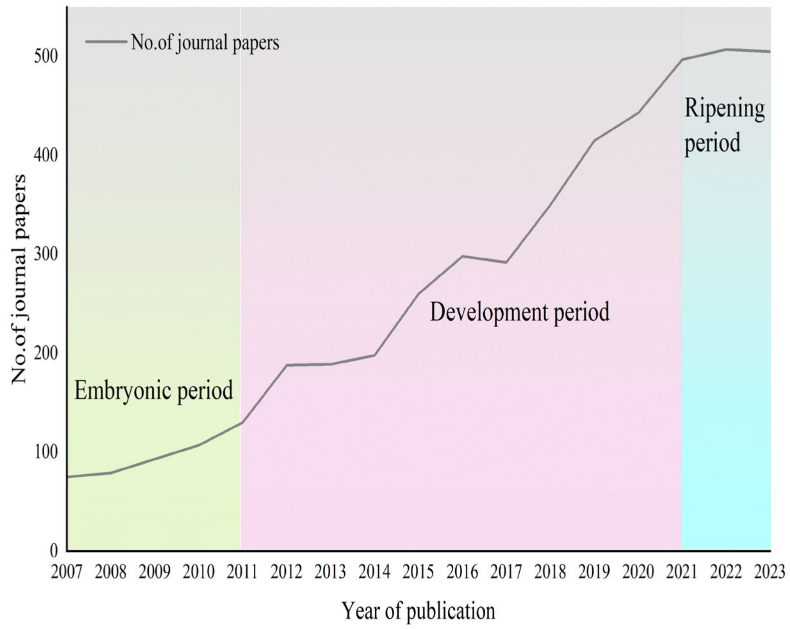

Figure 2: Three stages of growth in the study of interdependent network robustness based on number of papers.

3.2. Author Analysis

The identification of core authors offers valuable insights into the leading scholars in a particular research field. A total of 21,245 authors were identified from the 4,627 journal articles retrieved. Following Price's law[46], which defines the relationship between the number of publications and the number of authors, we calculated the minimum publication threshold for an author to be considered prolific:

$$M = 0.749\sqrt{N_{\max}} = 0.749\sqrt{33} = 4.30 \approx 5 \tag{1}$$

Where *M* denotes the minimum number of publications for an author to be considered prolific, and *Nmax* represents the number of papers published by the most prolific author. In this case, the most prolific author, Cao, Jinde, has published 33 papers. Consequently, the threshold for identifying core authors was set at a minimum of five papers, with 156 authors meeting this criterion.

However, core authorship should not be determined solely by the quantity of publications, as the quality of their work must also be taken into account. To address this, total citation count was integrated as an additional metric, and a composite index was calculated using the following formula:

$$CI = 0.5 \times \frac{N}{\overline{N}} + 0.5 \times \frac{TC}{\overline{TC}} \tag{2}$$

Where *CI* denotes the composite index, *N* is the number of papers published by an author, $\overline{N}$ is the average number of papers published by the 156 authors, *TC* is the total number of citations received by the author, and $\overline{TC}$ is the average citation count of these 156 authors.

This calculation identified 11 authors with a composite index greater than 2, who were designated as core authors (Table 1). Collectively, these 11 authors published 196 journal articles, representing 4.24% of the total 4,627 articles retrieved. In comparison, the 156 prolific authors collectively published 1,154 journal articles, accounting for 24.62% of the total output. This figure is significantly lower than the 50% predicted by Price's law, suggesting that the field of interdependent network robustness research has not yet developed a stable core group of leading scholars. Of these core authors, Shlomo Havlin leads with 29 journal articles and 5,931 citations, resulting in a composite index of 8.47. Eugene H. Stanley ranks second with 31 papers and 5,369 citations, yielding a composite score of 7.99. Sergey V. Buldyrev ranks third with 9 journal articles and 4,409 citations, giving him a composite index of 5.45.

Table 1: Top 11 core authors in interdependent network robustness research.

Rank	Author	Number of journal papers	Times cited	Comprehensive index
1	Havlin, Shlomo	29	5,931	8.47
2	Eugene Stanley, H.	31	5,369	7.99
3	Sergey V Buldyrev	9	4,409	5.45
4	Cao, Jinde	33	2,293	4.75
5	Perc, Matjaz	16	2,245	3.55
6	Gao, Jianxi	14	1,492	2.58
7	Chen, Guanrong	11	1,616	2.52
8	Lu, JINHU	10	1,594	2.43
9	Verkhivker, Gennady	26	599	2.42
10	Yu, Wenwu	6	1660	2.23
11	Blüthgen, Nico	11	1,216	2.08

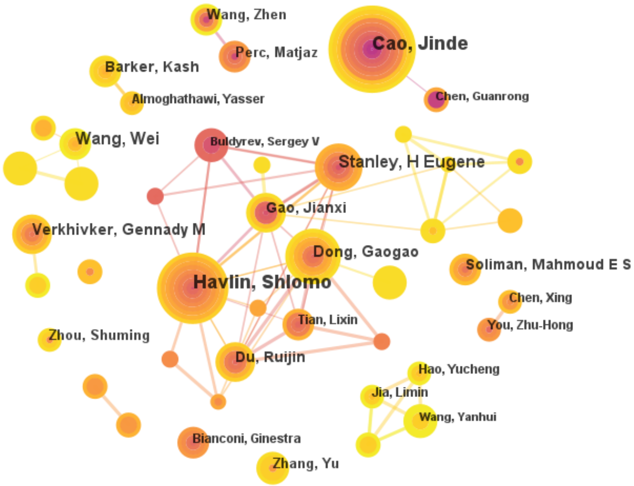

Figure 3: Co-occurrence network of authors in interdependent network robustness research.

The author co-occurrence network, generated using CiteSpace, highlights the key contributors and collaboration patterns within the field of interdependent network robustness research (Fig. 3). The size of the nodes represents the frequency of an author's appearance in the dataset, and the lines between nodes denote collaborative relationships. The most central figure in the network is Shlomo Havlin, whose extensive contributions, particularly in collaboration with Sergey V. Buldyrev and H. Eugene Stanley, have significantly shaped the field. These core authors form a closely-knit group, representing foundational work in the area. Jinde Cao is another prominent figure, with his contributions to control theory applications in network robustness being widely recognized[47,48], often working alongside collaborators such as Guanrong Chen. Several smaller clusters also emerge, indicating active research groups that are contributing to specific subfields. Authors like Gao Jianxi serve as connectors between different clusters, suggesting interdisciplinary collaborations that bridge theoretical and applied research. The presence of emerging researchers, such as Wei Wang and Yucheng Hao, indicates the growing diversity and expansion of the field, with newer scholars beginning to establish their influence. Overall, the network reflects a highly collaborative and international research landscape, with a mix of well-established thought leaders and rising voices, contributing to the ongoing evolution of the field.

3.3. Analysis of Affiliated Research Institutions

Institutions with more than 1% of the total publication output were designated as core research institutions (Fig. 4). Upon analyzing the publication output of these core institutions, the Chinese Academy of Sciences (CAS) emerges as the leading contributor with 193 published papers. Although the average citation rate per paper is moderate at 42.64, the substantial volume of publications underscores CAS's pivotal role in advancing research in this domain. The University of California system ranks second with 141 papers, and its notable average citation rate of 101.82 per article further emphasizes its substantial academic influence. Likewise, the Centre National de la Recherche Scientifique (CNRS) and Harvard University have contributed 100 and 83 papers, respectively. Harvard's average citation rate of

93 per paper further highlights the high quality and significant impact of its contributions to this field. In contrast, the Indian Institute of Technology (IIT) system and the University of London, despite contributing a comparable number of papers (71 each), exhibit significant differences in citation impact. Specifically, the IIT system's relatively low citation rate of 13.2 suggests that its research may target more specialized areas. Institutions such as Boston University and Harvard Medical School have demonstrated a profound academic impact, with average citation rates of 133.29 and 111.53 per paper, respectively. These figures indicate that their research consistently produces high-quality outputs and exerts considerable influence in the field. Furthermore, although institutions such as Bar-Ilan University and the Spanish National Research Council (CSIC) have published fewer papers, their citation rates remain notably high. Bar-Ilan University, in particular, achieves an impressive 127.82 citations per paper, indicating that its research holds significant academic value and strong potential for further application.

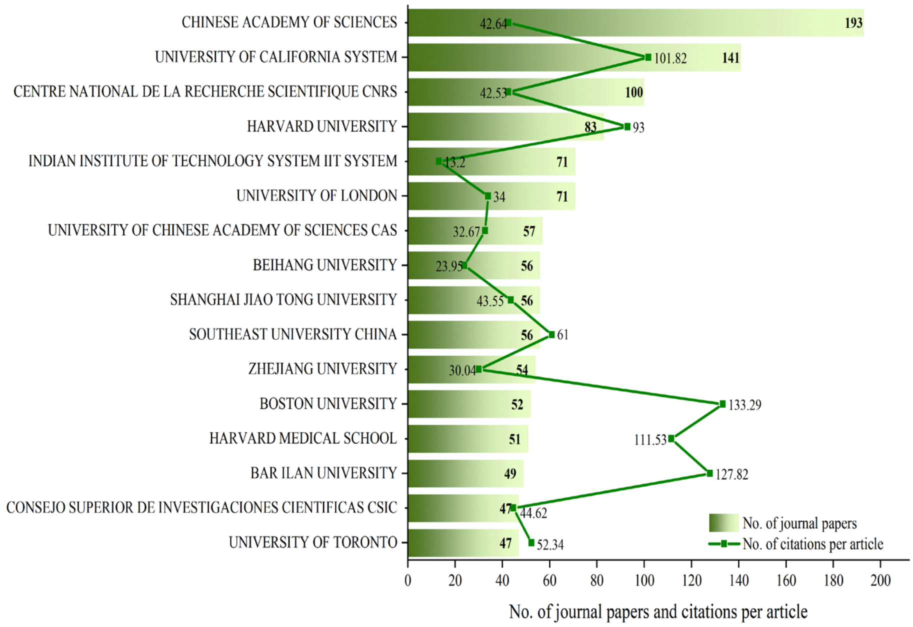

Figure 4: Major research institutions in the field of interdependent network robustness research.

Overall, the contributions of these leading institutions to the study of interdependent network robustness exhibit considerable variation. While some prioritize publication volume, others, despite fewer papers, make a substantial impact through high citation rates. This reflects the diverse research approaches and influence within the field.

3.4. Analysis of Literature Sources and Research Fields

The 4,627 articles retrieved come from 1,076 journals, of which 708 published only 1-2 articles, while a significant proportion is concentrated in the remaining 368 journals. Bradford's law categorizes journal articles into core, related, and peripheral zones[49]. The core zones were identified using Bradford's law, expressed as:

$$Q = 2\ln(e^{E} P) \tag{3}$$

Where Q represents the number of core zones, E is Euler's constant (0.5772), and P is the maximum number of articles among all journals. In this study, the calculation results in Q=2ln(1.781×195)=11.7, indicating that the top 11 journals represent the core publishers (Table 2). These 11 journals collectively published 948 articles, representing 20.49% of the total retrieved literature.

These journals span a wide array of research areas, such as physics, computational biology, bioinformatics, and broader topics in science and technology. The top three journals, PLOS ONE, Scientific Reports, and Physica A, contribute 4.21%, 3.54%, and 2.44% of the total articles, respectively. These journals span interdisciplinary fields and are predominantly classified in Q1 or Q2 according to Journal Citation Reports (JCR), reflecting their substantial influence and high research quality in the field.

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Table 2: Ranking of top 11 core journals.

Rank	literature sources	Number of journal papers	Research areas	Journal Citation Reports partition	Proportion of total (%)
1	PLOS ONE	195	Science Technology Other Topics	Q1	4.21
2	SCIENTIFIC REPORTS	164	Science Technology Other Topics	Q1	3.54
3	PHYSICA A STATISTICAL MECHANICS AND ITS APPLICATIONS	113	Physics	Q2	2.44
4	PHYSICAL REVIEW E	91	Physics	Q1	1.97
5	PLOS COMPUTATIONAL BIOLOGY	63	Biochemistry Molecular Biology；Mathematical Computational Biology	Q1	1.36
6	BMC BIOINFORMATICS	58	Mathematical Computational Biology	Q1	1.25
7	CHAOS	57	Mathematics；Physics	Q1	1.23
8	PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	57	Science Technology Other Topics	Q1	1.23
9	BMC GENOMICS	55	Biotechnology Applied Microbiology；Genetics Heredity	Q2	1.19
10	INTERNATIONAL JOURNAL OF MOLECULAR SCIENCES	50	Chemistry	Q2	1.08
11	NATURE COMMUNICATIONS	45	Science Technology Other Topics	Q1	0.97

3.5. Highly Cited Literature Analysis

The robustness of interdependent networks is a critical research focus that spans multiple disciplines, as evidenced by the high citation counts of key papers in this field. Among the 4,627 articles retrieved, 53 have been classified as highly cited, indicating their significant influence in advancing the understanding of network robustness and related domains. This study highlights the top ten most-cited papers from these 53 highly cited works, showcasing the pivotal research contributions within the field (Table 3).

One of the most impactful papers, "Catastrophic cascade of failures in interdependent networks" by Buldyrev et al. (2010)[50], has been cited over 3,000 times. This foundational work, published in Nature, explores how cascading failures in interconnected systems can lead to catastrophic breakdowns, establishing a cornerstone for subsequent research in interdependent network analysis. Similarly, papers such as Yu et al.'s (2009)[51] "On pinning synchronization of complex dynamical networks", cited 875 times, contribute to the understanding of network control mechanisms and stabilization, a concept critical for ensuring the robustness of these systems. The influence of systems biology on network analysis is also evident, as seen in Zhou et al.'s (2019)[52] "Metascape provides a biologist-oriented resource for the analysis of systems-level datasets", which, with over 6,400 citations, highlights the growing importance of large-scale data analysis tools for understanding complex systems, including interdependent networks. Similarly, Kanehisa et al.'s (2016)[53] "KEGG as a reference resource for gene and protein annotation", with over 4,000 citations, underscores the interconnectedness of biological and technological networks, providing insights into how similar methodologies can be applied across different domains.

These highly cited papers reflect the interdisciplinary nature of robustness studies, spanning topics such as cascading failures, biological network modeling, and synchronization. Together, they form a cohesive body of work that drives forward the theoretical and practical understanding of interdependent networks, illustrating both the challenges and strategies for maintaining their robustness in the face of various disruptions.

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Table 3: Ranking of top 10 highly cited literature.

Rank	Title	Authors(Year)	Source Title	Total Citations
1	Metascape provides a biologist-oriented resource for the analysis of systems-level datasets[52]	Zhou, Yingyao et al.(2019)	NATURE COMMUNICATIONS	6412
2	KEGG as a reference resource for gene and protein annotation[53]	Kanehisa, Minoru et al.(2016)	NUCLEIC ACIDS RESEARCH	4149
3	Catastrophic cascade of failures in interdependent networks[50]	Buldyrev, Sergey V. et al.(2010)	NATURE	3008
4	Macroscopic Multifunctional Graphene-Based Hydrogels and Aerogels by a Metal Ion Induced Self-Assembly Process[54]	Cong, Huai-Ping et al.(2012)	ACS NANO	1005
5	Architecture of the human interactome defines protein communities and disease networks[55]	Huttlin, Edward L. et al.(2017)	NATURE	954
6	Pinning complex networks by a single controller[56]	Chen, Tianping et al.(2007)	IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS I-REGULAR PAPERS	877
7	On pinning synchronization of complex dynamical networks[51]	Yu, Wenwu et al.(2009)	AUTOMATICA	875
8	Plant-Pollinator Interactions over 120 Years: Loss of Species, Co-Occurrence, and Function[57]	Burkle, Laura A. et al.(2013)	SCIENCE	750
9	Target identification using drug affinity responsive target stability (DARTS)[58]	Lomenick, Brett et al.(2009)	PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	680
10	Electrical and synaptic integration of glioma into neural circuits[59]	Venkatesh, Humsa S. et al.(2019)	NATURE	637

4. Research Hotspots and Emerging Trends

4.1. Visual Analysis of Co-Occurring Keywords

The visual analysis of co-occurring keywords reveals key trends and focal points in the research on interdependent networks. By examining keyword frequency and centrality, critical themes underlying the field are identified (Fig. 5). Stability, having the highest centrality (449), emerges as the most influential concept, highlighting its critical role in network dynamics and robustness studies. Following stability are keywords such as expression (343), system (315), and model (311), reflecting the interdisciplinary approach that encompasses biology, engineering, and theoretical modeling in exploring network structures and behaviors. Keywords such as dynamics (290), identification (274), and interaction network (264) emphasize the study of dynamic interactions in complex systems, which are crucial for predicting and managing cascading failures. The term complex network (260) further demonstrates the research community's focus on studying intricate, multilayered systems. Although broad, the keyword network

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(259) highlights the essential nature of this research across multiple disciplines, spanning biological systems to technological infrastructures. Keywords like robustness (202) and interdependent network (197) point directly to the core focus of this study, specifically understanding how networks maintain functionality under disruptive conditions. Furthermore, terms such as cascading failure (158), vulnerability (77), and resilience (66) reflect ongoing concerns about the fragility and recovery potential of interconnected systems.

Overall, the co-occurring keyword analysis underscores the field's focus on stability, robustness, and the complex interactions within networks. This body of research is highly interdisciplinary, with applications in biology, engineering, and social systems, reflecting a broad effort to advance the understanding and management of interdependent systems.

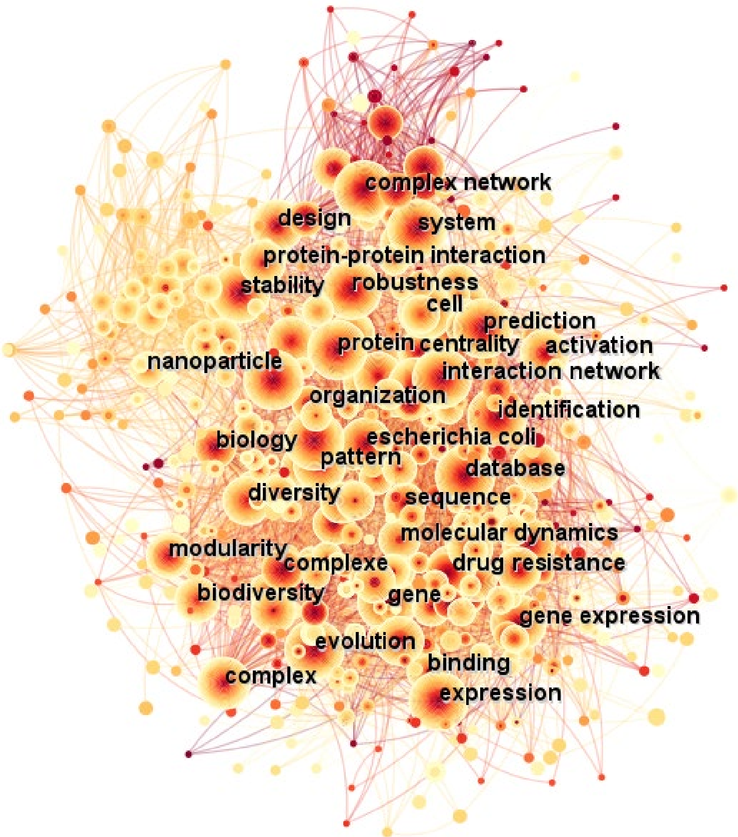

Figure 5: Keyword co-occurrence network for dependency network robustness study.

4.2. Cluster Analysis

The keyword cluster analysis reveals several key research areas within the field of interdependent networks. Six distinct clusters were identified, each representing a unique focus (Table 4). Cluster 0 emphasizes genetic expression and survival mechanisms, particularly in critically ill patients, linking biology with complex network analysis. Cluster 1 highlights advancements in nanomaterials and thermal energy systems, focusing on performance improvements in composites and solar-thermal energy applications. Cluster 2 delves into ecological networks, community interactions, and biodiversity, showing how multilayer networks apply to biological systems. Cluster 3, closely aligned with the core topic of interdependent networks, addresses cascading failures, social equity, and the dynamics of power transmission systems, demonstrating the relevance of this research to both social and physical infrastructures. Cluster 4 focuses on complex systems and stability, including neural networks and water distribution, while Cluster 5 explores molecular and protein structures, emphasizing binding mechanisms and energy distribution at the molecular level.

Together, these clusters showcase the interdisciplinary nature of interdependent network research, with applications ranging from biology and ecology to energy systems and complex infrastructure, reflecting a broad interest in understanding and optimizing the robustness of networks across different domains.

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Table 4: Keyword clustering results of the research literature on robustness of interdependent networks retrieved based on web of science platform from 2007-2023.

Cluster ID	Cluster topic	Number of key words	Main research focus
0	Gene expression and survival in critically ill patients	9	Expression; gene; survival; respiratory syndrome; critically ill patient | identification; saccharomyces cerevisiae; genome; checkpoint; agent
1	Nanostructured composites and thermal properties	9	Composite; performance; oxide; nanostructure; reduction | thermal conductivity; graphene aerogels; solar-thermal energy conversion; phase change composites; anode
2	Ecological networks and biodiversity	9	Ecological network; community; architecture; biodiversity; plant | ecological networks; species roles; multilayer networks; host-parasitoid interactions; habitat diversity
3	Interdependent networks and cascading failures	9	Interdependent networks; prisoners dilemma game; importance measure; social vulnerability; social equity | cascading failure; interdependent network; power transmission lines; systems biology; cascades propagation
4	Complex systems and network stability	9	System; stability; complex; ring domain; ubiquitylation | complex networks; chaotic neural networks; delay coupling; node vulnerability; water distribution networks

4.3. Burst Analysis of Keywords

The Burst analysis[60], conducted using CiteSpace, provides valuable insights into the temporal evolution of key research trends within the field of interdependent network robustness from 2007 to 2023(Fig. 6). The analysis identifies periods during which specific keywords experienced a significant surge in citations, indicating shifts in research focus and emerging themes within the domain.

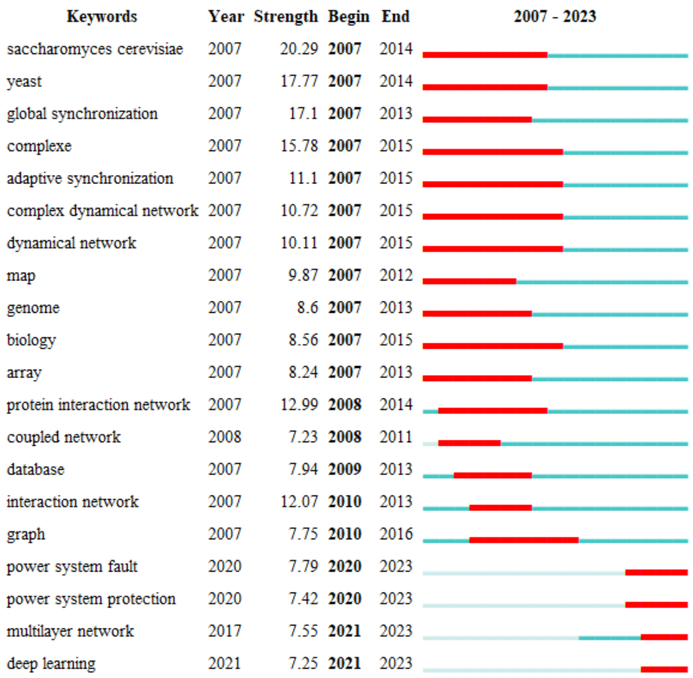

Figure 6: Top 20 keywords with the strongest citation bursts in network robustness studies.

From the results, it is clear that early research (2007-2015) was heavily centered around biological networks and systems biology, as indicated by high-strength bursts for keywords like saccharomyces cerevisiae (20.29), yeast (17.77), and protein interaction network (12.99). This reflects the initial

ISSN 2616-5775 Vol. 7, Issue 10: 105-118, DOI: 10.25236/AJCIS.2024.071015

integration of biological network theory into broader interdependent network analysis, where biological systems served as a fundamental framework for exploring robustness, failure, and interaction dynamics. As the field progressed, the focus gradually shifted towards more generalizable network structures and dynamics, as seen with bursts for terms like global synchronization (17.11), complex network (15.78), and adaptive synchronization (11.1). These keywords highlight an expanding interest in how different types of networks—both biological and technological—respond to external perturbations, with particular attention to synchronization and stability across interconnected systems. In recent years (2016-2023), the analysis reveals a growing emphasis on technological networks, as demonstrated by bursts in keywords such as power system fault (7.79) and power system protection (7.42), as well as the increasing prominence of multilayer network (7.55) and deep learning (7.25). This shift indicates a transition from purely theoretical studies to applied research, particularly in infrastructure resilience and the integration of advanced computational techniques like machine learning to optimize network robustness[61,62].

Based on these findings, future research in the robustness of interdependent networks is likely to focus on several key areas: (1) Application of Machine Learning and AI[63]: The recent burst in keywords like deep learning suggests that advanced algorithms will play a crucial role in predicting network failures and optimizing resilience. Future studies could explore the integration of artificial intelligence with interdependent network models to enhance real-time decision-making and risk management. (2) Evolving Network Topologies: While multilayer networks are well-studied, understanding how dynamically evolving networks, such as social or transportation systems, maintain robustness is crucial. Research should explore how networks adapt to structural changes (new nodes or links) and external shocks (natural disasters, cyberattacks) while identifying strategies to preserve stability. (3) Sustainable Infrastructure Networks[64]: With growing concerns about climate change, there is an urgent need to develop resilient and eco-friendly infrastructures. Future research should investigate how to design interdependent systems—like energy grids or water networks—that not only withstand disruptions but also minimize environmental impact, integrating sustainability into network resilience studies. (4) Cross-Domain Interdependencies[65]: As networks become more interconnected across domains (biological, technological, social), understanding how failures propagate between sectors is vital. Research should focus on identifying critical nodes where failures could spread across multiple systems and devise strategies to protect these key points, ensuring overall system stability. (5) Cyber-Physical System Resilience[66]: Increasing reliance on interconnected digital and physical systems heightens the risk of cyber-physical threats. Future studies should examine how networks like smart grids or autonomous systems can be safeguarded from cyberattacks, combining technical and policy insights to address these vulnerabilities effectively.

5. Conclusions

This study presents a bibliometric analysis of 4,627 articles on interdependent network robustness, published between 2007 and 2023, using CiteSpace software. The analysis reveals key trends, contributions, and challenges in the field. The findings show that the field has gained increasing attention, driven by the complexity of modern systems and the vulnerability of interconnected infrastructures to disruptions. The publication output analysis reveals three phases: steady growth (2007–2011), rapid expansion (2012–2020), and stabilization (2021–2023). These phases suggest that the field has matured, with established theoretical foundations. While institutions like the Chinese Academy of Sciences and the University of California system are key contributors, and journals such as PLOS ONE and Scientific Reports are major publication outlets, a cohesive core group of authors has yet to form, indicating the field is still evolving in leadership.

The analysis of highly cited literature and keyword networks reveals two primary research trajectories: theoretical exploration and real-world application. Theoretical advances focus on network modeling, failure propagation, and robustness optimization. These studies offer foundational insights into network dynamics and have led to the development of analytical frameworks. Empirical studies, often driven by infrastructure failures, apply these models to improve the robustness of power grids, transportation, and other vital systems. Keyword clustering and burst detection reveal emerging hotspots such as resilience strategies for cascading failures, the impact of climate change and cyberattacks on critical infrastructure, and optimization of resource allocation in interdependent networks. These topics highlight the field's growing interdisciplinarity, as big data, machine learning, and complex systems theory reshape the research landscape.

Despite significant progress, several gaps and uncertainties remain. A key challenge is the diversity of models, assumptions, and methods, which complicates cross-study comparisons and the development

ISSN 2616-5775 Vol. 7, Issue 10: 105-118, DOI: 10.25236/AJCIS.2024.071015

of universal solutions. As networks grow more complex, robust empirical validations of theoretical models are increasingly necessary. Future research must also address emerging threats such as artificial intelligence, cyber warfare, and extreme climate events as technological advancements accelerate.

In summary, this paper provides a comprehensive review of the current state of interdependent network robustness research, highlighting key trends, challenges, and future directions. The identification of core journals, institutions, and gaps in author collaboration offers valuable insights for both new and established scholars in the field. This research aims to stimulate further exploration of interdependent network robustness, contributing to the resilience and stability across multiple domains, including biology, finance, and society.

Acknowledgments

This work was supported by the General Program of the Natural Science Basic Research Plan in Shaanxi Province (Project No. 2024JC-YBMS-581).

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