

ORIGINAL

Research Trends and Collaboration Patterns in Quantum Internet: A Bibliometric Mapping Using Biblioshiny, VOSviewer, and CiteSpace

Tendencias de investigación y patrones de colaboración en la Internet cuántica: un mapeo bibliométrico utilizando Biblioshiny, VOSviewer y CiteSpace

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ABSTRACT

Introduction: quantum Internet has emerged as a transformative technological frontier, attracting increasing global research attention. Its development spans foundational physics, cryptography, network engineering, and applied technologies, demanding systematic evaluation of scholarly progress.

Objective: this study aims to present a comprehensive bibliometric analysis of Quantum Internet research, identifying publication trends, influential contributors, collaborative networks, and evolving thematic directions.

Method: data were retrieved from the Scopus database and analyzed using Biblioshiny, VOSviewer, and CiteSpace. The study examined publication growth, author and journal influence, country-level collaborations, bibliographic coupling, keyword co-occurrence, and thematic evolution.

Results: findings indicate steady growth in publications since 2016, peaking in 2024 with 130 documents. Leading contributors include Angela Sara Cacciapuoti, Marcello Caleffi, Laszlo Gyongyosi, and Stephanie Wehner, while prominent publication outlets are Physical Review Letters, Physical Review A, Scientific Reports, and New Journal of Physics. Country-level analysis highlights the United States, China, the United Kingdom, Italy, and Japan as primary research hubs, with strong international collaborations. Network analyses reveal 15 author and 10 journal clusters, underscoring interdisciplinary connections. Bibliographic coupling and keyword co-occurrence identify critical themes such as quantum key distribution, entanglement distribution, quantum memory, blockchain, and cybersecurity, alongside emerging areas like quantum IoT and quantum machine learning. Thematic maps show a shift from theoretical constructs to application-driven studies, integrating artificial intelligence and advanced sensing. Trend analyses confirm growing attention to scalability, security, and interdisciplinary applications, though gaps remain in resource optimization, experimental validation, and integration with classical infrastructures.

Conclusions: this analysis provides a knowledge framework and practical insights into the intellectual and conceptual structure of Quantum Internet research. By mapping influential contributors, core themes, and research gaps, the study supports academics, policymakers, and industry in making strategic investments and advancing future research in this rapidly evolving field.

Keywords: Quantum Internet; Bibliometric Analysis; Biblioshiny; Vosviewer; Citespace.

RESUMEN

Introducción: la Internet cuántica ha emergido como una frontera tecnológica transformadora que atrae creciente atención mundial. Su desarrollo abarca la física fundamental, la criptografía, la ingeniería de redes y las tecnologías aplicadas, lo que exige una evaluación sistemática del progreso científico.

Objetivo: este estudio tiene como propósito presentar un análisis bibliométrico integral de la investigación en Internet cuántica, identificando tendencias de publicación, contribuyentes influyentes, redes de colaboración y direcciones temáticas en evolución.

Método: se recopilaron datos de la base de datos Scopus y se analizaron mediante Biblioshiny, VOSviewer y CiteSpace. El estudio examinó el crecimiento de las publicaciones, la influencia de autores y revistas, las colaboraciones a nivel de países, el acoplamiento bibliográfico, la coocurrencia de palabras clave y la evolución temática.

Resultados: los hallazgos indican un crecimiento constante en las publicaciones desde 2016, alcanzando su punto máximo en 2024 con 130 documentos. Los principales contribuyentes incluyen a Angela Sara Cacciapuoti, Marcello Caleffi, Laszlo Gyongyosi y Stephanie Wehner, mientras que las revistas más destacadas son Physical Review Letters, Physical Review A, Scientific Reports y New Journal of Physics. El análisis a nivel de países resalta a Estados Unidos, China, Reino Unido, Italia y Japón como polos de investigación con sólidas colaboraciones internacionales. Los análisis de redes revelan 15 clústeres de autores y 10 de revistas, subrayando las conexiones interdisciplinarias. El acoplamiento bibliográfico y la coocurrencia de palabras clave identifican temas críticos como la distribución de claves cuánticas, la distribución de entrelazamiento, la memoria cuántica, blockchain y ciberseguridad, junto con áreas emergentes como el IoT cuántico y el aprendizaje automático cuántico. Los mapas temáticos muestran un cambio de los marcos teóricos hacia estudios impulsados por la aplicación, integrando inteligencia artificial y tecnologías avanzadas de detección. Los análisis de tendencias confirman un creciente interés en la escalabilidad, la seguridad y las aplicaciones interdisciplinarias, aunque persisten vacíos en la optimización de recursos, la validación experimental y la integración con infraestructuras clásicas.

Conclusiones: este análisis proporciona un marco de conocimiento y perspectivas prácticas sobre la estructura intelectual y conceptual de la investigación en Internet cuántica. Al mapear contribuyentes influyentes, temas centrales y vacíos de investigación, el estudio apoya a académicos, responsables de políticas e industria en la realización de inversiones estratégicas y en el avance de futuras investigaciones en este campo en rápida evolución.

Palabras clave: Internet Cuántica; Análisis Bibliométrico; Biblioshiny; Vosviewer; Citespace.

INTRODUCTION

The Quantum Internet (QI) represents a cutting-edge frontier in communication technology, designed to exploit the principles of quantum mechanics to achieve unparalleled levels of security, computational power, and efficiency.^(1,2) Unlike traditional internet protocols, which transmit data as binary bits, QI utilizes quantum bits (qubits) that can exist in superposition and become entangled, enabling phenomena such as quantum teleportation and unconditionally secure communication through quantum key distribution (QKD).^(1,3) This capability promises revolutionary applications across secure banking, defence communication, distributed quantum computing, and large-scale sensing networks.^(2,4) As countries and institutions worldwide invest heavily in this domain, through initiatives like the U.S. National Quantum Initiative, the EU Quantum Communication Infrastructure, and China's Micius satellite, the research output on QI is expanding rapidly and becoming increasingly diverse.⁽⁵⁾

The interdisciplinary nature of QI makes it both promising and complex.⁽⁶⁾ It draws expertise from quantum physics, electrical and computer engineering, information theory, cryptography, and even policy and ethics.^(7,8) Early research explored theoretical models and protocols for entanglement distribution, while recent work focuses on overcoming technical barriers such as decoherence, building robust quantum repeaters, and integrating QI with existing classical networks.^(8,9) Journals like Nature, Science Advances, and Physical Review Letters regularly publish influential articles, highlighting the fast pace and competitive nature of this field.^(7,10) Such diversity, coupled with rapid technological changes, creates an urgent need for systematic mapping of the literature to guide researchers, industry, and policymakers.⁽¹¹⁾

Given this surge, bibliometric analysis has become an essential approach to synthesize and assess QI research comprehensively.^(12,13) Bibliometrics applies quantitative methods to bibliographic data, publications, citations,

and keywords to evaluate research performance and map intellectual structures.^(14,15) Unlike narrative reviews that focus on conceptual summaries, bibliometric studies uncover trends, relationships, and emerging fronts using evidence-driven techniques.^(16,17) By identifying prolific authors, leading institutions, and collaborative networks, bibliometric analysis provides valuable strategic insights.^(18,19) It also highlights influential papers and intellectual clusters that define the trajectory of the field, helping to prioritize research agendas and funding directions.⁽²⁰⁾

Previous reviews on the Quantum Internet have often been highly technical and narrow in scope, focusing on specific aspects such as QKD protocols, cryptographic frameworks, or device-level implementations.^(3,6,9) For instance, Mehic et al.⁽⁸⁾ provide a comprehensive survey of quantum cryptography in 5G networks, but their analysis remains limited to technical applications without capturing the broader intellectual and collaborative landscape. Similarly, Chen et al.⁽³⁾ examined cryptographic applications, yet did not address interdisciplinary linkages or global collaboration trends. These examples illustrate the need for a holistic bibliometric mapping that moves beyond technical overviews to reveal research dynamics, thematic evolution, and international engagement.

Despite its potential, bibliometric work on QI remains scarce. Previous reviews have often been technical and narrow, addressing topics like QKD or specific hardware components, without capturing the broader research ecosystem.⁽²¹⁾ This study seeks to fill this gap by analyzing QI research holistically, identifying knowledge hotspots and evolving trends.^(22,23) It also examines interdisciplinary linkages, gaps in regional participation, and thematic shifts that could influence the design of future networks.^(24,25) The findings are intended to support scholars entering the field, innovators seeking commercialization opportunities, and policymakers shaping national quantum strategies.

METHOD

This study focuses on research outputs on the Quantum Internet indexed in SCOPUS databases, covering journal articles, reviews, and conference proceedings.⁽²⁶⁾ It spans the period from the earliest conceptual studies to the most recent publications, thereby capturing the full developmental arc.^(27,28) The scope includes topics like entanglement distribution, quantum repeaters, QKD protocols, quantum memory, and network architectures.^(29,30) By incorporating data globally, the study accounts for both established and emerging research hubs. The integration of quantitative performance measures and network visualizations ensures a detailed understanding of contributors, themes, and collaborations.^(16,31)

The primary objective of this bibliometric study is to present a comprehensive, data-driven overview of the research landscape on the Quantum Internet, highlighting its historical growth, current status, and emerging directions. It aims to quantify publication trends and citation impacts to assess productivity and influence; identify leading authors, institutions, journals, and countries contributing to the field; examine co-authorship and collaboration networks to reveal knowledge-sharing patterns; and analyze keyword co-occurrences and thematic clusters to uncover dominant areas and research gaps. Additionally, the study seeks to map thematic evolution, detect citation bursts, and visualize intellectual structures using advanced bibliometric tools, thereby providing actionable insights for scholars, industry stakeholders, and policymakers engaged in shaping the future of Quantum Internet research.

To achieve these objectives, bibliometric techniques are employed to convert bibliographic records into interpretable knowledge maps.^(32,33) This involves performance indicators such as publication counts and citations, and science mapping techniques such as co-citation, bibliographic coupling, and co-word analysis.^(34,35) The approach provides both macro-level insights, including growth rates and geographic trends, and micro-level perspectives, including intellectual foundations and current research fronts.^(36,37) The analysis is designed not only to summarize existing knowledge but also to provide actionable insights for stakeholders in academia, industry, and policy.⁽³⁸⁾

Three widely used bibliometric tools are applied to ensure methodological rigor and rich visualization. Biblioshiny, an interactive web-based application for the R package bibliometrix, is used to manage data cleaning, descriptive analysis, and thematic mapping.^(39,40,41) Its strength lies in producing comprehensive summary statistics such as annual growth rates and author productivity and user-friendly graphics.⁽⁴²⁾ VOSviewer specializes in building and visualizing bibliometric networks, including co-authorship, citation, and co-occurrence maps.^(43,44) Its clustering algorithms reveal thematic groupings and relationships, while overlays highlight temporal evolution.^(45,46)

CiteSpace complements these tools by focusing on detecting emerging trends and research fronts.^(47,48) It uses algorithms to identify citation bursts, pivotal works, and thematic shifts across time slices, offering insights into how the field evolves.^(49,50) The combination of these three tools enhances the robustness of the analysis: Biblioshiny for data management and descriptive analytics, VOSviewer for network visualization, and CiteSpace for trend detection and intellectual structure analysis.^(51,52) Together, they create a holistic picture of the QI research domain, supporting evidence-based conclusions and recommendations.

The bibliometric data for this study were retrieved from the Scopus database, which is widely recognized for its extensive coverage of scholarly literature.^(26,53) The search strategy was formulated using the query TITLE ABS KEY “Quantum Internet” to ensure the retrieval of publications where the term appeared in the title, abstract, or keywords.

This search yielded 707 documents comprising journal articles, conference papers, book chapters, and other document types. To ensure methodological rigor and transparency, the PRISMA framework was employed to guide the screening and selection process.⁽⁵⁴⁾ All 707 records were screened, and 79 were excluded due to document type, including reviews, books, notes, conference reviews, editorials, short surveys, letters, and errata. The remaining 628 documents were assessed for eligibility and included for detailed analysis, consisting of 396 articles, 210 conference papers, and 22 book chapters, as illustrated in the PRISMA flow diagram.

After the screening process, the refined dataset was cleaned and prepared for analysis. The complete bibliographic metadata including author details, affiliations, citations, keywords, and references were exported in CSV and RIS formats to ensure compatibility with advanced bibliometric software. These files formed the basis for subsequent analysis using Biblioshiny, VOSviewer, and CiteSpace, enabling performance evaluation, network mapping, and visualization of trends. The final dataset was retrieved from Scopus on 15 July 2025, covering the period 2000-2025. The search strategy included the terms “Quantum Internet” OR “quantum network” OR “quantum internetnetwork”. Records were refined by removing duplicates, standardizing author and affiliation details, and verifying metadata accuracy. We retained articles, conference papers, and book chapters as primary research outputs, while excluding reviews, editorials, and notes; this choice emphasizes original contributions, though we acknowledge the limitation. For analysis, thresholds were set at five documents per author (co-authorship), ten citations (bibliographic coupling), and five occurrences (keywords). Indicators examined included publication trends, citation impact, prolific contributors, journal influence, international collaborations, and thematic evolution. This systematic approach ensured comprehensive coverage of the Quantum Internet research landscape, providing robust data for uncovering thematic structures, collaboration patterns, and emerging research fronts.

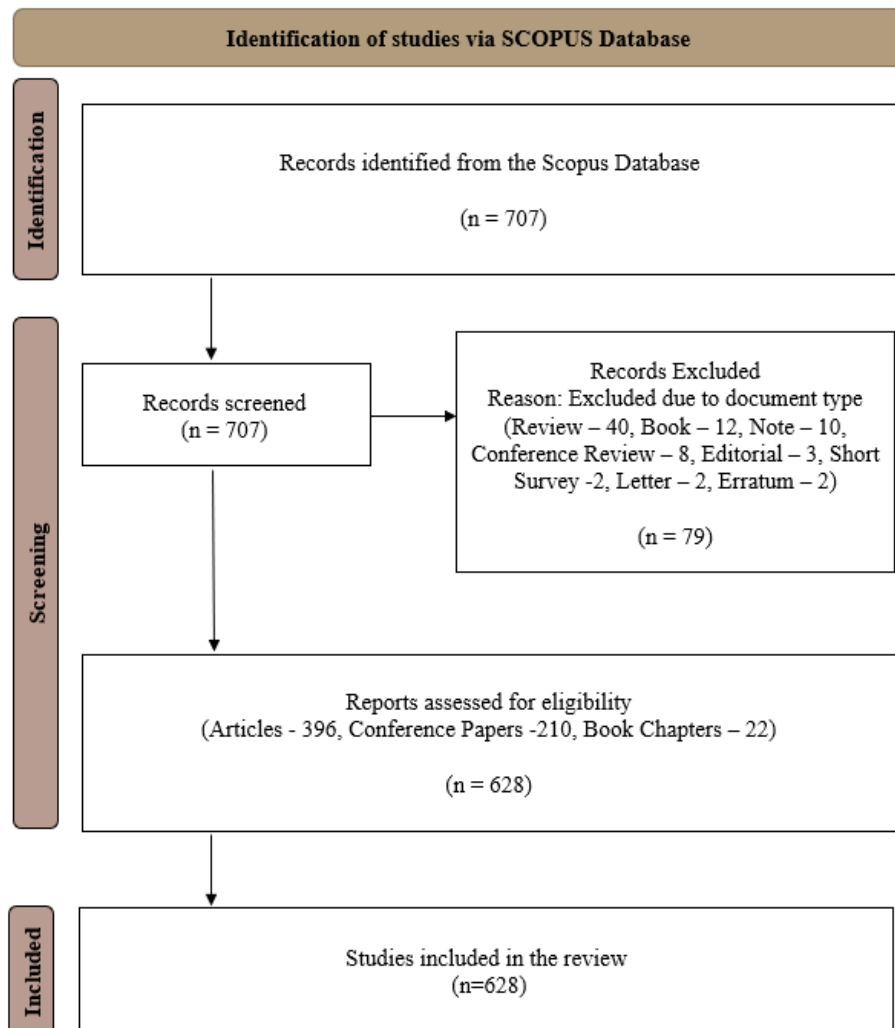


Figure 1. PRISMA flow diagram used to identify, screen, and include papers in the bibliometric analysis

RESULTS

Main information of the investigation

The bibliometric dataset on Quantum Internet research spans the years 2000 to 2025 and comprises 628 documents sourced from 259 journals, books, and other scholarly outlets. The field demonstrates a robust annual growth rate of 18,39 percent, with an average document age of 3,49 years, indicating that much of the research is relatively recent. On average, each document has received 22,43 citations, showing a moderate impact, and collectively, the dataset references 21 709 sources. Content-wise, the literature features 3251 Keywords Plus terms and 964 author-supplied keywords, showcasing the diversity and evolving terminology of the field. Contributions come from 1959 authors, of whom 50 produced single-authored works, while 64 documents overall were single-authored. Collaboration is notable, with an average of 4,72 co-authors per document and 26,75 percent of the works involving international partnerships. In terms of document types, journal articles dominate with 396 publications, followed by 210 conference papers and 22 book chapters, illustrating a balance between theoretical development and dissemination through conferences and edited volumes.

Annual Scientific Productions

The annual scientific production shows a slow start between 2000 and 2010, with minimal output of one or two papers annually and several years showing no publications. A gradual increase appears after 2011, reaching five papers in 2011 and 2012 and eight in 2014, followed by some fluctuation in 2015. A significant rise is evident from 2016 onwards, with a sharp upward trend particularly visible after 2018 when the output reached 22 papers, continuing to grow steadily to 31 in 2019 and 50 in 2020. The momentum strengthened further with 73 publications in 2021 and 83 in 2022, culminating in a peak of 111 papers in 2023 and the highest output of 130 papers in 2024. The count for 2025 stands at 68 publications up to July, suggesting continued strong activity. Overall, the data reflect an accelerating growth trajectory, highlighting the rapidly expanding interest and investment in Quantum Internet research over the past decade.

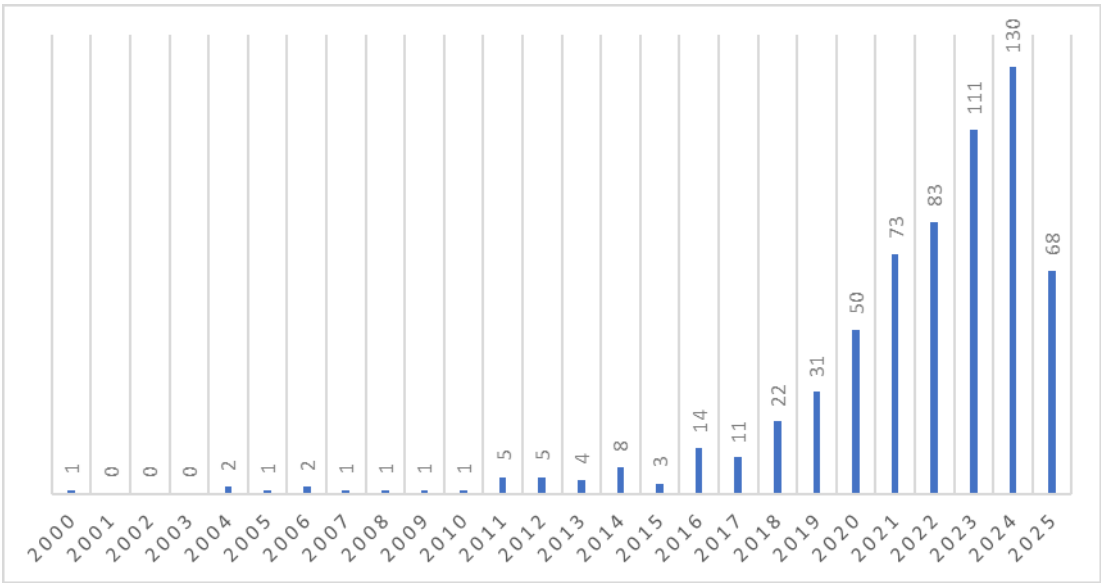


Figure 2. Annual scientific production from 2000 to 2025

Most Relevant Authors

Table 1, the most relevant authors highlights a core group of highly productive contributors. Angela Sara Cacciapuoti, Marcello Caleffi, and Laszlo Gyongyosi lead the field with 27 publications each, demonstrating their consistent and significant involvement in advancing the theoretical and practical aspects of Quantum Internet. Sandor Imre closely follows with 24 works, and W. J. Munro and Kae Nemoto with 17 works each demonstrate strong contributions, especially experimental and applied research. Stephanie Wehner, the quantum communication and networking notable figure, contributes 15 works that further highlight her impact on the development of this research field. Coming after the first group of contributors is the second group comprising Riccardo Bassoli and Frank H. P. Fitzek, each contributing 14 works, and Rodney Van Meter contributing 12 works, revealing active participation in both scholarly research work and collaborative research initiatives. As a group, the group constitutes the intellectual kernel that powers originality and research scholarship on the Quantum Internet studies, guiding its development and propagation across the globe.

Table 1. Most relevant authors	
Authors	Articles
Cacciapuoti, Angela Sara	27
Caleffi, Marcello	27
Gyongyosi, Laszlo	27
Imre, Sandor	24
Munro, W.J.	17
Nemoto, Kae	17
Wehner, Stephanie	15
Bassoli, Riccardo	14
Fitzek, Frank H. P.	14
Van Meter, Rodney	12

Network visualization of co-citation of cited authors

Figure 3 provides a comprehensive overview of the co-citation network of cited authors, structured into 15 distinct clusters, each showing a thematic or intellectual domain. Cluster 0, labeled High-Fidelity Entanglement Distribution, is the largest with 81 members and a silhouette value of 0,745, showing moderate cohesiveness. This cluster focuses on high-quality entanglement, memory, and network design. Notable citing articles include Singh 2021 on applications and challenges, Li 2024 on layered protocols, and multiple contributions by Gyongyosi 2020 on resource prioritization and dynamics. The most cited authors here are Van Meter with 131 citations, Caleffi with 111, Kozlowski with 88, and Dur with 85, indicating strong emphasis on network-level engineering and protocol development for reliable entanglement sharing across quantum networks.

Cluster 1, Metropolitan Fibre Network, is a group of 72 members whose silhouette value is 0,699. It demonstrates design and scaling quantum networks based on fibers, frequently in cities or regions. Notable works to cite include Singh 2021 on quantum computing and communications, Yang 2023 on quantum communications, and Gyongyosi 2020 on network dynamics. Notable authors Yin with 88 citations, Liao with 56, and Khatri with 38 lead this cluster, highlighting infrastructure and metropolitan network integration towards quantum communications. Cluster 2, First Loophole-Free Bell Test, is a 71-member group with a larger silhouette value of 0,859. This shows a technically consistent group working on experimental foundational verification. Notable works to include include Gyongyosi 2020 on network dynamics, Singh 2021 on quantum computing and communications, and Yang 2023 on quantum communications. Briegel with 87 citations, Einstein with 35, and Kwiat with 15 are the most prominent names here, which show experimental and historical origins verifying quantum mechanics principles towards communication technologies.

Cluster 3, Entanglement Distribution, consists of 69 members with a 0,782 silhouette. It is about spreading entangled states through networks and maintaining strong connections. The cluster references several works from Gyongyosi 2020 and Singh 2021 and relies heavily on survey and experiment works. The top authors are Wehner with 214 citations, Kimble with 194, and Pirandola with 164, revealing their influential contributions to protocol design and experiment arrangements. Cluster 4, Key Distribution, with 64 members and 0,717 silhouette, is about cryptographic bases and QKD. Illustrative articles are Singh 2021, Yang 2023, Khatri 2022, and Gyongyosi 2019. Those who lead the contributions include Ekert with 77 citations, Lo with 45, and Scarani with 39, showing the strong focus on safe communication and key interchange methods as foundational pillars to quantum network construction.

Cluster 5, Dinger Cat, accommodates 61 members with a 0,845 silhouette. It merges theoretical constructs and distributed computing features. High-citing works include Sheng 2010 on entanglement concentration and Caleffi 2024 on distributed computing surveys. Highly cited works include Bennett with 242 citations and Nielsen with 114 citations, pointing towards the usefulness of baseline theoretical models and algorithmic schemes. Cluster 6, Quantum Internet, with 52 members having a 0,864 silhouette, deals with integrated topics on architecture and noise-scaled optimisation. Repeating citations include Gyongyosi 2020 series on memories, noise stability, and architecture. Highly citing researchers such as Cacciapuoti with 107 citations, Shor with 88 citations, and Preskill with 51 citations dominate, pointing towards the integration of architectural design, fault tolerance, and algorithmic theory required to scale quantum internets.

Beyond these core areas, Cluster 7, Single-Sided Optical Microcavity with 28 members and a silhouette of 0,788, focuses on device-level studies with authors like Wootters with 54 and Eisert with 18, demonstrating niche but significant research on quantum photonics and optical components. Cluster 8, Other Device with 19 members and a silhouette of 0.974, and Cluster 9, Quantum Network with 18 members and a silhouette of 0,971, represent specialized hardware and protocol-driven networks, with Duan with 55 and Gisin with 95 respectively

leading. Cluster 10, Random Quantum Network with 17 members and a silhouette of 0,933, captures theoretical models with contributors like Acin with 18, while Cluster 11, Magneto-Mechanical Quantum Interface with 15 members and a silhouette of 0,98, points toward hybrid systems with Cirac with 29 as a central figure. Each of these smaller clusters showcases the field's diversity, ranging from abstract models to specific device technologies.

Finally, Cluster 12, Computing with 13 members and a silhouette of 0,995, and Cluster 13, Near-Term Quantum Device with 9 members and a silhouette of 0,997, are highly coherent but small, emphasizing computing paradigms and short-term hardware advances, with authors like Brennen and Chaneliere taking the lead. Cluster 16, Dynamics with 7 members and a silhouette of 1, is the smallest but most internally consistent, highlighting modeling and dynamic behaviors of entangled networks, where Amer with 8 citations and Sax with 4 appear prominently. Together, these clusters paint a layered picture of Quantum Internet research: from theoretical physics and cryptographic methods to device engineering and metropolitan network design. The co-citation patterns confirm a rich interplay of theory, experimentation, and application, underscoring how diverse scholarly efforts are converging to shape the future of quantum communications.

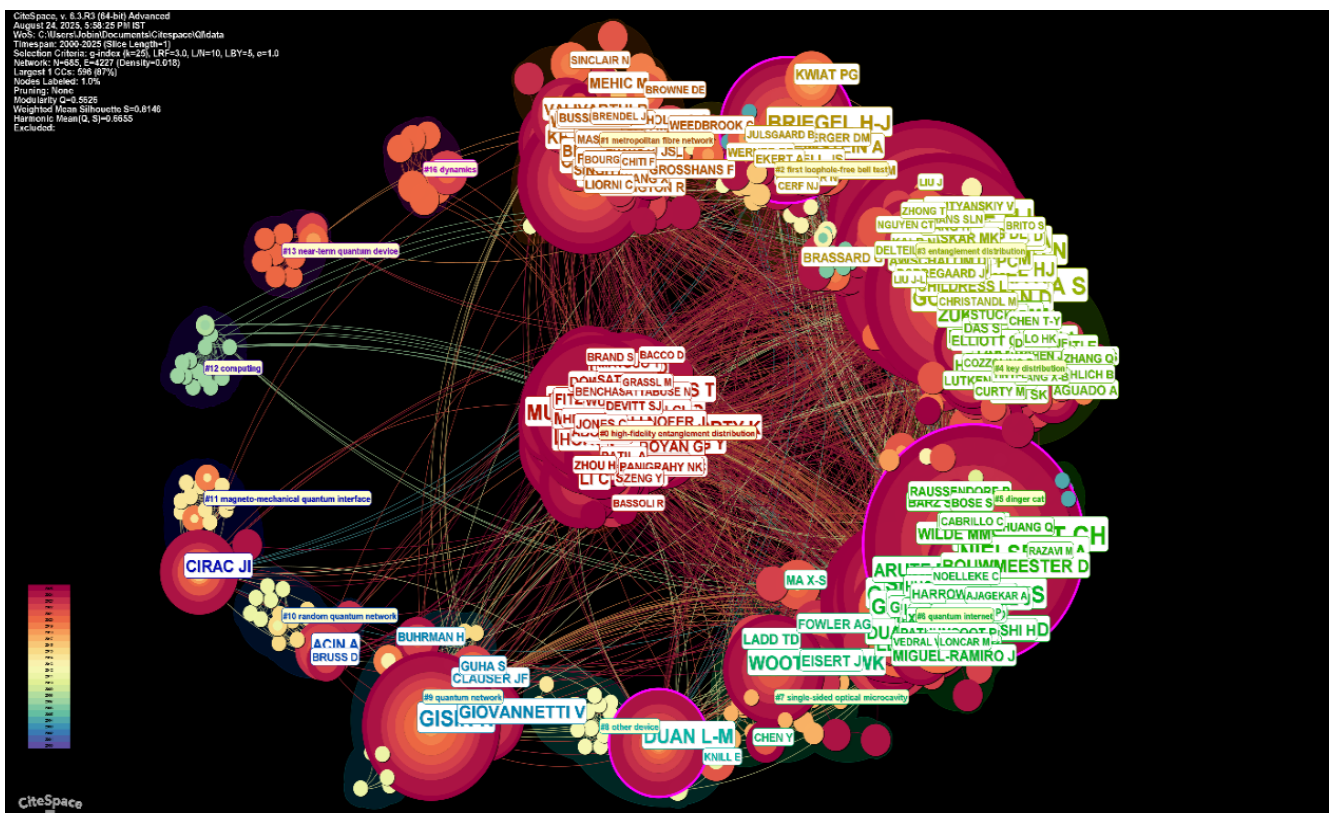


Figure 3. Network visualization of co-citation of cited authors

Most Relevant Sources

Table 2 highlights the most relevant publication sources, showing the platforms that have contributed the highest number of articles. Proceedings of SPIE, The International Society for Optical Engineering leads with 23 publications, implies the importance of engineering and optical technology conferences for disseminating experimental and applied work. Scientific Reports follows with 21 articles, showing its role as a multidisciplinary journal hosting high-impact studies across theoretical and applied domains. IEEE Network and IEEE Transactions on Quantum Engineering, with 20 and 17 articles respectively, emphasize the growing focus on network architecture, communication protocols, and engineering solutions for quantum systems. Optics Infobase Conference Papers with 16 publications and Physical Review A with 15 indicate strong engagement from optics and physics communities in foundational studies. Other key journals, including IEEE Journal on Selected Areas in Communications and NPJ Quantum Information (13 each), as well as Quantum Science and Technology and Quantum Information Processing, contribute significantly to both technical and theoretical advancements. Collectively, these sources illustrate a multidisciplinary research environment, bridging physics, optics, engineering, and information science to advance the Quantum Internet.

Table 2. Most Relevant Sources	
Sources	Articles
Proceedings of SPIE - The International Society for Optical Engineering	23
Scientific Reports	21
IEEE Network	20
IEEE Transactions on Quantum Engineering	17
Optics Infobase Conference Papers	16
Physical Review A	15
IEEE Journal on Selected Areas in Communications	13
NPJ Quantum Information	13
Quantum Science and Technology	12
Quantum Information Processing	11

Timeline Network Visualization of Co-Citation of Cited Journals

Figure 4 illustrates the co-citation network of cited journals, organized into 10 major clusters, each representing a specific thematic or disciplinary focus. Cluster 0, titled Bell-State Measurement, is the largest with 98 members and a silhouette value of 0,706. This cluster represents journals that frequently publish studies related to foundational quantum experiments, entanglement verification, and measurement systems. Key citing works include contributions from Khatri, Jennewein, and Pirker, which emphasize satellite-based communication and long-distance quantum networking. The most cited journals in this cluster are Journal of Modern Optics and Quantum Science and Technology, indicating their strong influence in experimental optics and photonic implementations critical to quantum communication infrastructure.

Cluster 1, titled Interoperable Protocol, consists of 81 members having a silhouette value of 0,794, show strong coherent research on the development of protocols and interoperability toward quantum networks. This cluster's intellectual base is built on the top journals like Physical Review Letters, having 95 citations, Physical Review A, having 86 citations, and Nature Photonics, having 58 citations. The visibility of the New Journal of Physics and Scientific Reports is an added testament to the strong connection between theoretical breakthroughs and experimental confirmation. These journals have accommodated seminal contributions by Gyongyosi and others on the stability of entanglement, efficiency of the memory, and noise-scaled optimality toward quantum communication systems serving the mainstay pillars on which this cluster is built.

Cluster 2, Classical Communication, comprised 72 members and had a silhouette value of 0,697. This represents a key intersection point among classical principles of networking and the emerging quantum paradigms. This cluster houses top journals such as IEEE Communications Surveys and Tutorials, Computer Networks, and Quantum Information Processing that regularly publish thorough reviews and algorithmic schemes towards resource optimisation, entanglement routing, and hybrid configurations. The cluster exemplifies the way classical communication theories are being re-purposed towards quantum scenarios, representing the developmental phase in the literature where the networks join classical and quantum regimes. Likewise, Cluster 3 and Cluster 4, falling under the umbrella term Quantum Internet, incorporate journals such as Nature, Science, Physical Review X, and IEEE Access, occupying the top spots in citations with counts of 300+ in certain instances. The clusters exemplify the dominant role played by the multidisciplinary journals and the top-impact journals towards characterizing the theoretical and the applied facets inherent to the Quantum Internet.

Lesser but strongly specific clusters reinforce the depth of the thematic coverage. Cluster 5, on Quantum Repeater, constitutes 46 members with an inner silhouette of 0,954, testifying to tight inner consistency. It encompasses journals like New Journal of Physics and Quantum Science and Technology that offer a venue for research on entanglement swapping, error correction, and repeater protocols vital to quantum networks that scale. Similarly, Cluster 6, whose title is based on the term Quantum Fourier, stresses algorithmic preliminaries and quantum computing methods, citing seminal works like Quantum Computation and Quantum Information by Nielsen and Chuang. Clusters 7 to 9 exploring Resource Prioritization, Quantum Teleportation Protocol, and First Loophole-Free Bell Test confirm the indicators on the specific but critical research areas. The clusters refer to journals like Scientific Reports, EPJ Quantum Technology, and IEEE Journal on Selected Areas in Communications, evidencing special effort toward the optimised distribution of entanglements, enhanced teleportation fidelity, and the experimental confirmation of quantum theory.

Overall, figure 4 reveals a closely interconnected journal network where multidisciplinary journals like Nature, Science, and Physical Review coexist with field-specific ones like Quantum Science and Technology,

Optics Express, and IEEE Access. The trend towards clustering indicates the progression of the research on the Quantum Internet from theoretical underpinnings and physics groundwork towards practical deployment scenarios and large-scale infrastructure. The prevalence of both generalist and specialist journals indicates the diversity of the field, which demands collaboration among the physics, engineering, and information science communities on an interdisciplinary level. This network visualization not only reveals the influential key journals but indicates the foci of the thematic convergence points, facilitating the future researchers to prioritize the key publication outlets corresponding to their research interests.

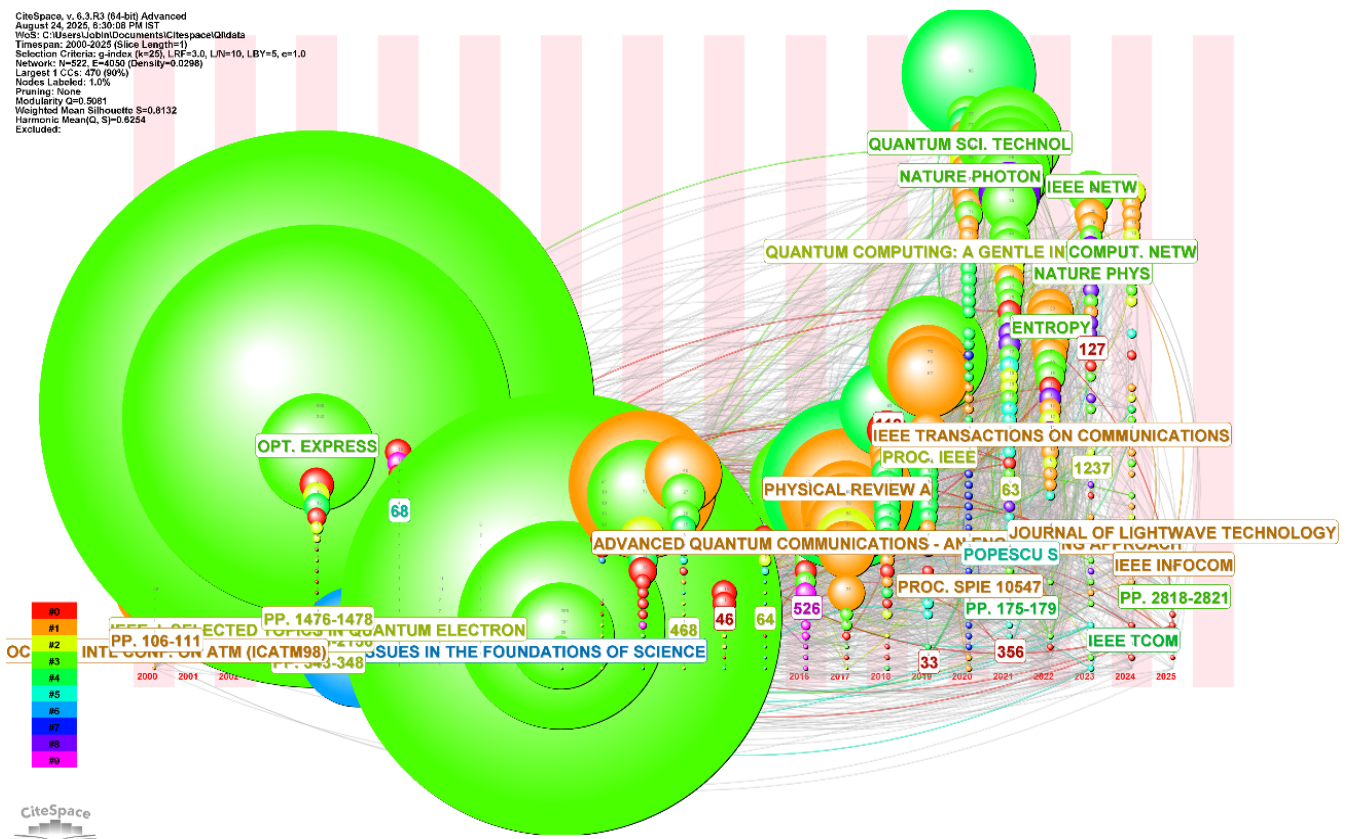


Figure 4. Network visualization of co-citation of cited journals

Network Visualization of bibliographic coupling of Documents

Figure 5 illustrates the network visualization of bibliographic coupling related to research on the Quantum Internet, based on a minimum citation requirement of 10. Out of 628 analyzed documents, 216 met this requirement. The resulting network consists of 213 items organized into six clusters, which are differentiated by color. Bibliographic coupling estimates the extent of similarity among documents based on the level of shared references shows thematic or intellectual linkages. The visualization identifies key contributors like Cacciapuoti, Caleffi, and Ren that appear as dense nodes within the red and green clusters, representing the strongest level of thematic cohesion and most frequent co-citation. The blue cluster houses key works such as those by Awschalom and Fukui, highlights experimental and hardware-centric research. On the other hand, yellow and purple clusters contain Pirker and Gyongyosi, indicates research on network architectures and entanglement. The fact that multiple clusters interlink suggests an inter- or even transdisciplinary research climate where theoretical-technology- and application-motivated themes come together.

The size and distribution of nodes in figure 6 reflect the level of influence, where larger nodes correspond to top-cited documents acting as intellectual hubs within the field. The tight grouping of clusters, especially red and green, reflects thematic convergences, presumably on early concepts, protocols, and building blocks toward the development of the Quantum Internet. Blue and yellow clusters placed toward the periphery indicate special subfields like hardware realization, experimental configurations, and security mechanisms. The occurrence of six separate clusters evidences the multidisciplinary character of the research on the Quantum Internet, where the contributions span from theoretical concepts and algorithmic developments to practical networking configurations and secure applications. This network visualisation thus evidences the field's diversity and coherence, revealing the way the shared citations forge connections across the heterogeneity of the research areas.

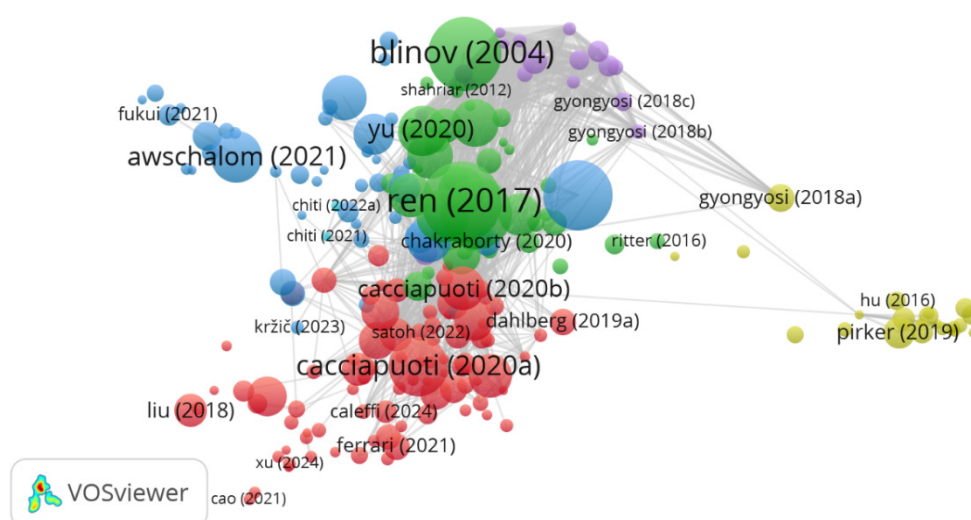


Figure 5. Network visualization of citations of documents

Co-occurrence of all keywords

Figure 6 illustrates the co-occurrence network of author keywords, highlighting the thematic connections within the research field. By applying a threshold of at least five occurrences, 45 keywords were chosen from a total of 964. These keywords are organized into seven clusters that differ in size and color. The most frequent term, quantum internet, sits in the core position with 195 occurrences due to its centrality and foundational status. Connected terms such as quantum communication, quantum networks, quantum computing, and quantum key distribution forge dense ties around the hub, shows strong interconnectedness among network design, cryptography, and computation. Clusters appearing closely interconnected reflect the tendency on the part of researchers to study these concepts as a group and highlight their complementary nature when building secure and scalable quantum infrastructures.

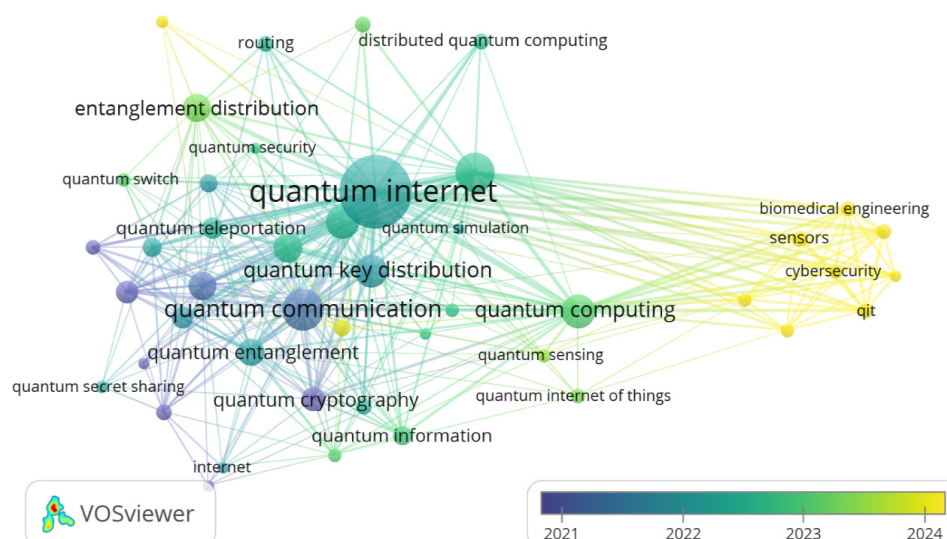


Figure 6. Co-occurrence of author keywords

The map also shows other significant, though minor, thematic regions. Phrases such as quantum entanglement, entanglement distribution, quantum cryptography, and quantum memory appear among key enablers of network functionality and security. Their locations near the core nodes reflect their significance in progressing core technologies such as key distribution, repeaters, and secure protocols. Rising areas such as quantum internet of things (QIoT), quantum simulation, and quantum sensing indicate expanding application spaces. The yellow cluster containing terms such as biomedical engineering, sensors, and cybersecurity reflects growing interest in cross-disciplinary merges, where quantum principles transfer from traditional communication into application

spaces such as healthcare and critical security systems.

The network color coding also indicates the chronology of the emergence of topics, such that early research (purple and blue) on core topics like quantum communication and quantum entanglement gives way to recent research (green and yellow) on cybersecurity, sensors, and biomedical engineering, shows diversification and maturation. The tight and dense linkages among the keywords indicate the collaborative and multiple-domain nature of research on the Quantum Internet, where breakthroughs in one domain—in particular, cryptography or computation—drive developments elsewhere. Overall, figure 7 shows an interconnected research landscape that is both strongly interconnected and quickly changing, where key technological pillars are reinforced by emerging cross-domain developments.

Thematic Evolution

Figure 7 illustrates the thematic evolution of Quantum Internet research across four distinct periods: 2000-2015, 2016-2021, 2022-2024, and 2025 onward. During the initial phase (2000-2015), foundational themes such as quantum entanglement and internet dominated, indicating the conceptual groundwork for integrating quantum principles into communication networks. Topics like entanglement and computational linguistics appeared, though the latter indicates some early, peripheral explorations. The second phase (2016-2021) shows diversification with the emergence of themes such as quantum cryptography, quantum memory, quantum networking, and internet of things, signaling efforts to address security, storage, and connectivity challenges. Notably, quantum entanglement remained central, indicating its continued relevance for practical implementations.

The third and fourth phases (2022-2024 and 2025 onward) mark a shift toward applied and performance-oriented research. Themes such as entanglement distribution, blockchain, learning systems, and quantum computing gained prominence between 2022 and 2024, showing technological integration and interdisciplinary expansion. In the latest phase (2025), high-impact topics like quantum communication, entanglement generation, error correction, quantum information technologies, and quantum key distribution (QKD) dominate, suggesting a focus on robust, scalable, and secure quantum networks. The consistent presence of quantum entanglement across all stages highlights its foundational role, while emerging themes such as quantum technologies and performance indicate the transition toward real-world deployment and optimization of Quantum Internet systems.

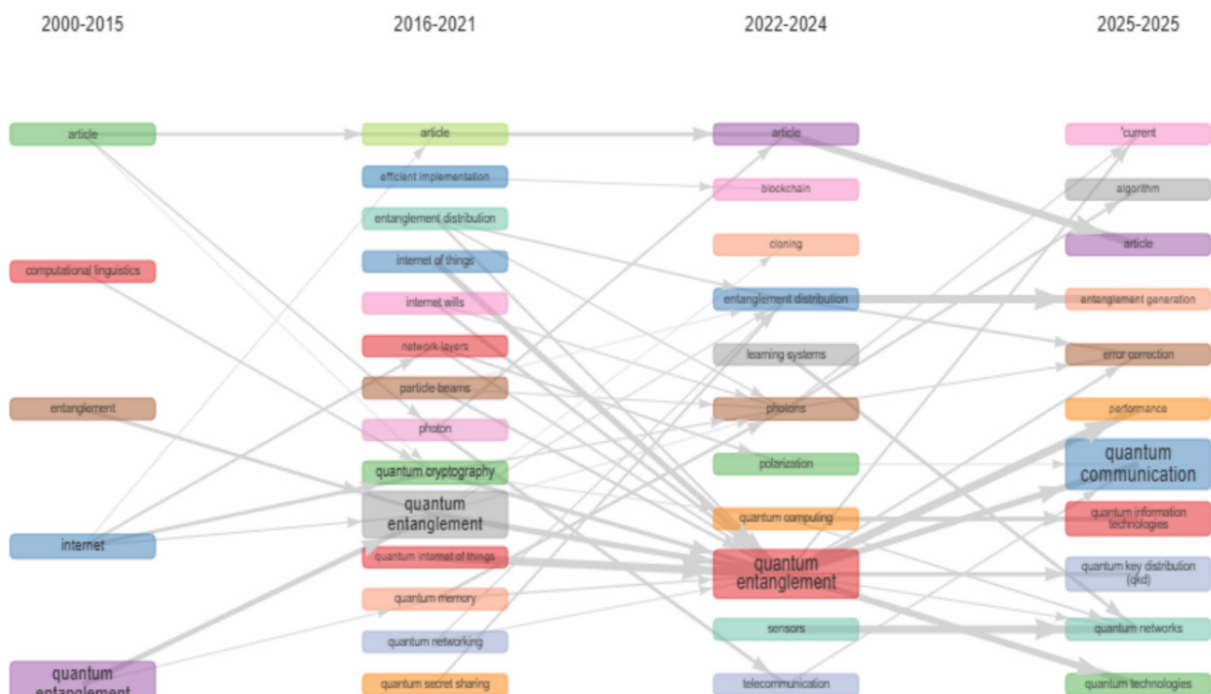


Figure 7. The thematic evolution of research on ethnomycology

Thematic Map

Figure 8 presents a thematic map of Quantum Internet research, illustrating the distribution of key topics across four quadrants based on their centrality (relevance) and density (development). The upper-right

quadrant, referred to as motor themes, includes well-developed and highly relevant topics that are central to the field. Here, themes such as multipartite entanglement, network topology, graph states, biomedical engineering, ICT, and sensors appear prominently. Their placement indicates strong structural importance and sustained interest, with multipartite entanglement and network topology representing the backbone of network design and scalability, while the presence of biomedical engineering and sensors suggests expanding interdisciplinary applications beyond communication, such as in healthcare and advanced sensing technologies.

The upper-left quadrant identifies niche themes, characterized by strong internal development but lower relevance to the overall network. This includes topics such as blockchain, quantum computation networks, 6G, security, networking, resource allocation, and quantum optics. These areas are more specialized and exploratory, demonstrating emerging or context-specific interests. While not central to Quantum Internet studies, they signify pockets of innovation, particularly blockchain and 6G, which point to potential integration of quantum technologies with next-generation communication and security frameworks.

This quadrant encircles fundamental and transversal themes that are inherent to the research field but possess moderate-level internal development. There are key terms such as quantum internet, quantum networks, quantum communication, entanglement distribution, quantum teleportation, quantum key distribution (QKD), network architecture, and quantum security. These constitute the building blocks of research on Quantum Internet and provide the conceptual and technological groundwork. Their centrality signifies their function of connecting varied subdomains, whereas their comparatively lesser density signifies that these areas remain perpetually dynamic, drawing wide-scale participation yet remaining receptive to additional conceptual fine-tuning and experiment.

Lastly, the bottom-left quadrant represents rising or falling themes with low centrality and low density. Examples involve quantum circuits, quantum Fourier transform, quantum signal processing, quantum error correction, quantum internet of things, and the generic term quantum. Their placement indicates that some among these subjects remain emerging and may take greater prominence when technologies continue to evolve, whereas others may indicate falling emphasis or specializations. The emergence of quantum internet of things signals an interest in bringing quantum functionality into IoT platforms and may signal future research frontiers. Figure 8 overall suggests that the research on Quantum Internet represents an active field where the core topics reside alongside experimental researches and interdisciplinary researches that keep opening multiple paths to growth and innovations.

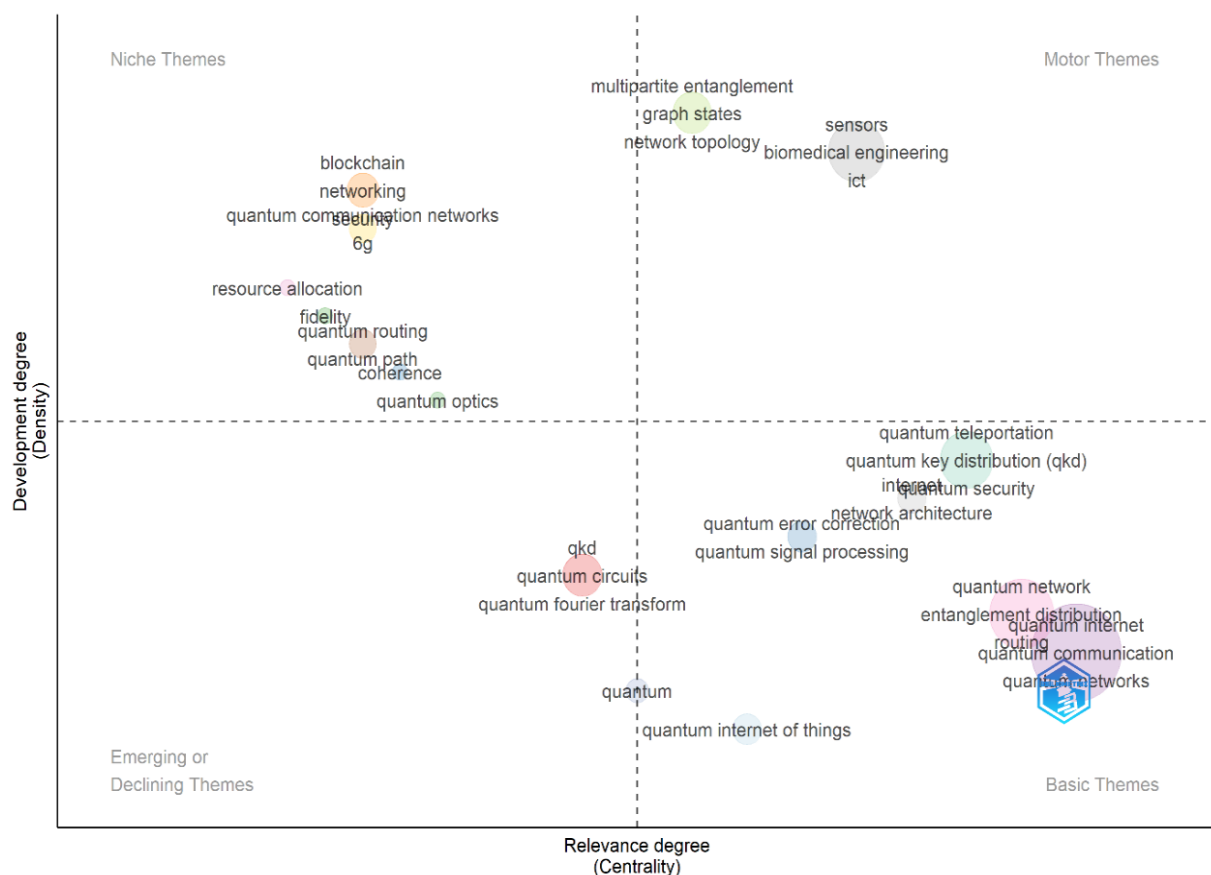


Figure 8. Thematic visualization of keywords

Trend Topics

Figure 9 illustrates the evolving research focus, highlighting key thematic trends over time. The earliest attention, around 2017 to 2019, was directed toward foundational areas such as quantum memory and quantum Shannon theory, shows efforts to establish the theoretical and storage principles needed for quantum communication systems. From 2020 onward, the focus broadened, with increasing prominence of topics like quantum cryptography, quantum repeater, and quantum networking, which are critical for ensuring security, scalability, and network functionality. Between 2021 and 2023, core themes including quantum internet, quantum communication, and quantum computing reached higher frequencies, indicating the consolidation of fundamental concepts and a shift toward implementation and system-level studies.

In the most recent period, particularly from 2023 to 2025, figure 10 shows the emergence of advanced and application-driven topics such as cybersecurity, quantum machine learning, and quantum sensors, which point to a growing interdisciplinary approach and emphasis on real-world use cases. Persistent focus on entanglement distribution and entanglement routing underscores ongoing efforts to overcome challenges in quantum network scalability and reliability. These trends indicate a dynamic and rapidly expanding research ecosystem, where foundational studies are increasingly complemented by applied research, aiming to integrate Quantum Internet technologies with broader domains like artificial intelligence, secure communications, and next-generation sensing.

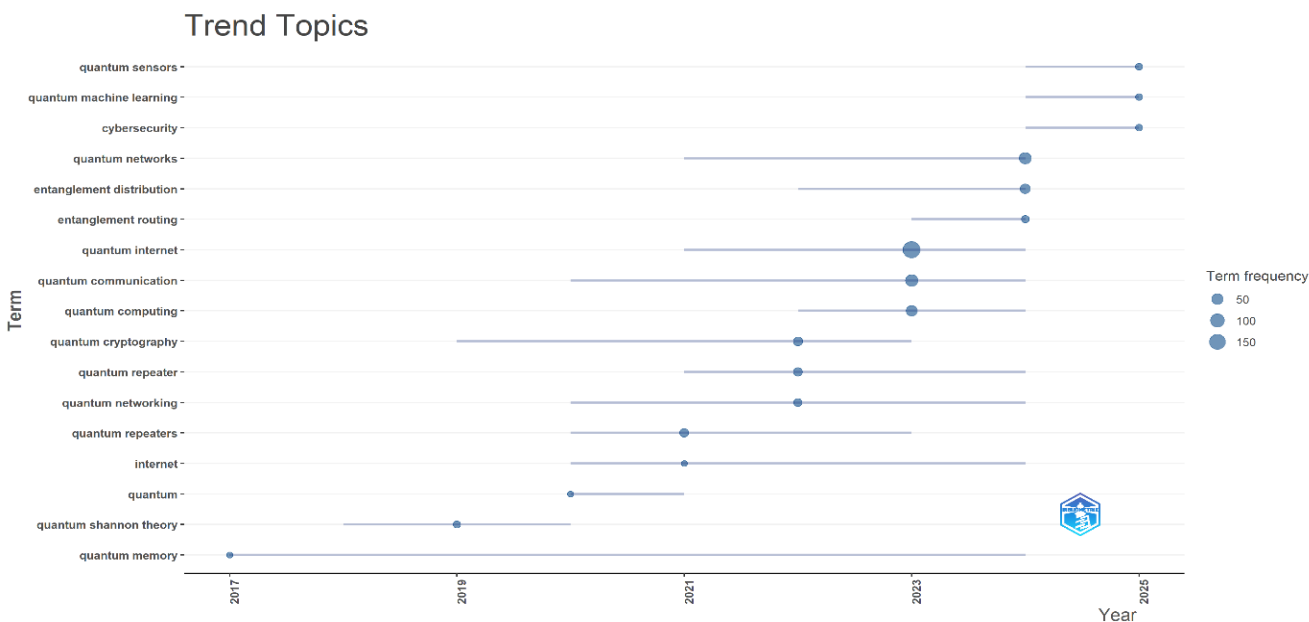


Figure 9. The evolution of trend topics in the Quantum Internet

Countries' Scientific Productions

Table 3 shows that the United States leads with 140 documents, demonstrating its strong investment and leadership in both theoretical and applied aspects of the field.

Table 3. Countries Scientific Productions	
Country/Territory	Documents
United States	140
China	86
United Kingdom	75
Italy	69
Japan	64
Germany	54
India	40
Netherlands	37
Canada	36
Hungary	32

China follows with 86 publications, highlights rapid growth and significant government and institutional support, particularly in quantum communication infrastructure. The United Kingdom and Italy, with 75 and 69 publications respectively, highlight Europe's active engagement, with a focus on protocol development and collaborative projects. Japan and Germany contribute 64 and 54 documents, showing consistent strength in experimental work, hardware, and network designs. Among emerging contributors, India stands out with 40 publications, signaling growing interest and developing capabilities, while the Netherlands and Canada have 37 and 36 documents, both recognized for specialized contributions in quantum networking and intercontinental collaborations. Hungary, with 32 publications, also shows noteworthy activity, indicating a strong research niche despite a smaller academic base. Together, these figures reveal that North America, Europe, and Asia are the primary hubs of Quantum Internet research, with diverse but complementary strengths across countries.

Timeline Network Visualization of Countries Collaborations

Figure 10 illustrates the network visualization of country collaborations, showing five clusters that highlight international partnerships and geographical strengths. Cluster 0, Quantum Information Technologies, is the largest with 13 members and a silhouette value of 0.635, emphasizing countries with strong research output in quantum technologies and experimental communication. Leading contributions come from works by Agarwal, Pepper, Valivarthi, and Azuma, addressing entanglement distribution, memory devices, and scalable protocols. The most cited countries in this cluster are China with 86 citations, Germany with 54, the Netherlands with 36, Canada with 33, and Spain with 21, showing a strong European and Asian presence. Cluster 1, Applications Functionalities, includes 12 members and focuses on applied research, implementation strategies, and networking challenges, with key works by Singh, Ribezzo, and Conti. Here, Italy, with 68 citations and India, with 41, dominate, followed by Poland, Ireland, and Saudi Arabia, indicating active participation from both European and Asian nations in application-driven studies and emerging collaborations.

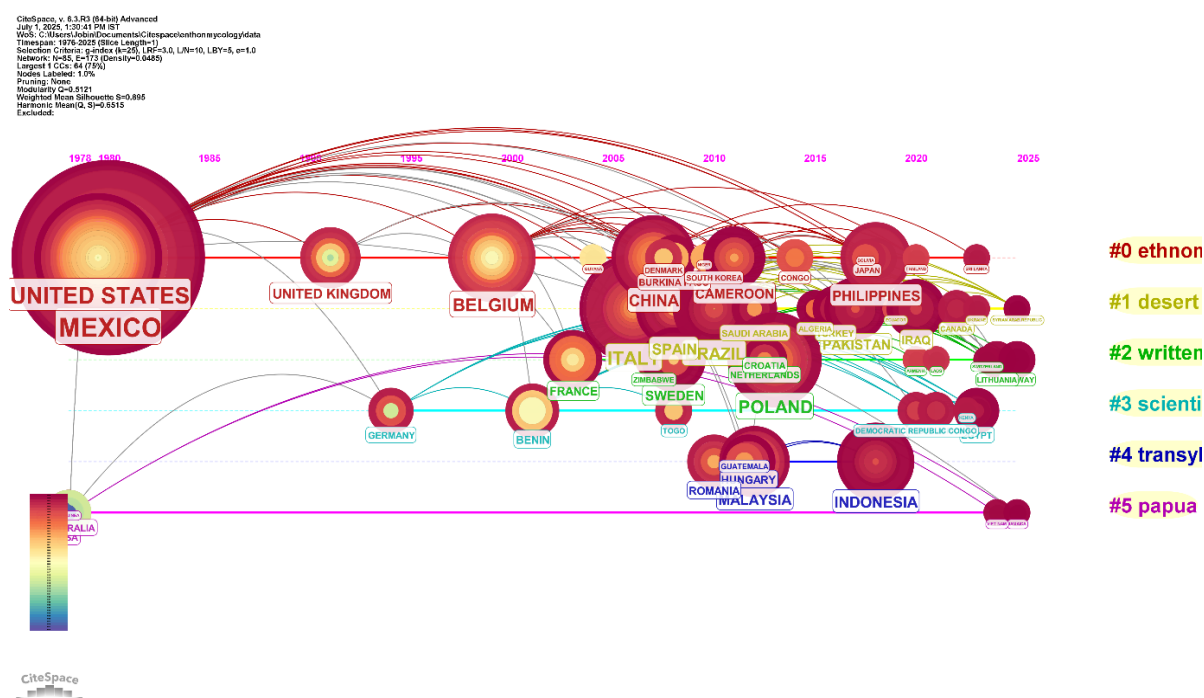


Figure 10. Timeline Network visualization of countries collaborations

Cluster 2, Quantum Information Technologies, comprises 10 members and has the highest individual citation strength, with the United States leading at 139 citations, showing its central role in innovation and protocol development. Other significant contributors are Japan with 61 citations, Australia with 21, France with 14, and Taiwan with 7, reflecting a wide international network supported by both established and emerging players. Cluster 3, Using Multi-Qubit Logical State, has 8 members, with the United Kingdom at 51 citations as the leading contributor, followed by South Korea, Luxembourg, Pakistan, and Malaysia, indicating targeted collaborations in advanced quantum coding and teleportation research. Cluster 4, Inter-European Quantum Network, though smaller with 6 members, reflects strong regional cooperation, with Austria leading at 21 citations, followed by Denmark, the Czech Republic, Romania, and Croatia, highlighting the European push toward interconnected infrastructure and network design. Collectively, these clusters demonstrate that while the United States and China lead in volume and influence, Europe and Asia are increasingly visible, with cross-country collaborations

driving both theoretical advancements and infrastructure-focused studies.

Taken together, these results trace a clear trajectory in the evolution of Quantum Internet research. Early contributions concentrated on foundational physics and entanglement verification, while subsequent studies advanced into network architectures, cryptographic frameworks, and device engineering. More recent clusters reveal an increasing emphasis on scalability, security, and integration with emerging domains such as quantum IoT and machine learning. The convergence of these strands reflects a field moving steadily from conceptual foundations toward practical deployment and interdisciplinary application, supported by strong global collaborations and diverse publication outlets.

DISCUSSION

The bibliometric mapping of Quantum Internet research reveals a field characterized by rapid growth, evolving themes, and strong international engagement. From a modest beginning in the early 2000s, the annual scientific production has shown a steep upward trend since 2016, peaking in 2024. The analysis of main information metrics underscores the vitality of the domain, with 628 documents across 259 sources, an annual growth rate exceeding 18 percent, and an average of 22 citations per document. Keywords and author collaboration metrics show a highly networked research environment, with nearly 27 percent international co-authorship. The most productive contributors, including Angela Sara Cacciapuoti, Marcello Caleffi, Laszlo Gyongyosi, Sandor Imre, and Stephanie Wehner, demonstrate high publication counts, strong citation impact, and centrality in co-citation and bibliographic coupling networks, underscoring their pivotal role in shaping both the theoretical and applied dimensions of entanglement distribution, network design, and security.

Network visualizations enrich this understanding by highlighting intellectual clusters and thematic coherence. Co-citation analysis of authors reveals 15 clusters, from high-fidelity entanglement to computing and dynamics, with notable influence from pioneers like Van Meter, Wehner, Kimble, Bennett, and Shor. The analysis of cited journals further emphasizes interdisciplinary depth, with Physical Review Letters, Physical Review A, Nature, and Scientific Reports serving as central hubs. Bibliographic coupling confirms six interconnected clusters, indicating cross-pollination between theory, protocols, hardware, and applications. The co-occurrence of author keywords illustrates core themes such as quantum internet, quantum communication, and QKD, alongside emerging directions like quantum sensors, machine learning, and biomedical integration. These networks reveal that foundational topics remain robust, while applied and interdisciplinary themes are gaining traction.

Temporal and thematic analyses shed light on how the field has matured. Thematic evolution highlights early dominance of foundational work on entanglement, cryptography, and memory, followed by diversification into blockchain, IoT integration, and AI-enhanced solutions. The thematic map shows a balance between motor themes like network topology and multipartite entanglement, basic themes like QKD and quantum teleportation, niche areas like blockchain and quantum optics, and emerging areas such as quantum circuits and quantum IoT. Trend topic analysis confirms this shift, with rising interest in cybersecurity, quantum machine learning, and sensing applications. Together, these patterns indicate a dynamic knowledge ecosystem where robust theoretical pillars coexist with exploratory and application-driven streams.

Geographical and collaborative patterns complement the thematic findings. The United States leads output and influence with 140 publications, followed by China, the United Kingdom, Italy, Japan, and Germany, while emerging players like India, the Netherlands, and Hungary also show significant activity. Country collaboration networks reveal five clusters, with North America, Europe, and Asia forming the core of global efforts. The United States and China dominate technological innovation, while European nations foster regional connectivity and diverse partnerships. Nations like India, Australia, and South Korea add to the diversity of the research landscape, particularly in applied and niche areas. These findings underscore that the Quantum Internet is not only a technological frontier but also a collaborative enterprise spanning continents, disciplines, and sectors, reflecting a strong blend of foundational science and practical ambition.

Research gaps and practical implications

The thematic map and trend topic analyses together point to several research gaps in Quantum Internet studies. While the motor themes of multipartite entanglement, network topology, and sensors are well-developed, the niche and emerging quadrants reveal areas needing deeper exploration. Topics like blockchain integration, 6G compatibility, and resource allocation show strong technical potential but remain peripheral, indicating a lack of large-scale experimental validation and theoretical unification. Similarly, foundational areas like QKD and quantum teleportation are central but still evolving, suggesting the need for more robust models addressing interoperability, error correction, and real-world deployment challenges. Emerging domains such as the quantum internet of things, quantum circuits, and hybrid computing are underrepresented, showing opportunities to expand the research focus toward industrial applications and integration with classical and AI-driven networks.

The practical implications of these findings are significant for researchers, policymakers, and industry. The

growth of cybersecurity, machine learning, and sensing as trend topics shows that Quantum Internet is moving beyond theory to real-world impact, demanding investments in interdisciplinary collaborations and testbeds. Institutions can prioritize funding and partnerships in niche but high-potential areas like blockchain-enabled quantum networks, space-based repeaters, and IoT integrations to gain a competitive edge. Standardization bodies and policymakers can use these insights to develop frameworks for secure and scalable quantum infrastructures, while industry stakeholders can focus on translating core concepts into deployable technologies. Addressing these gaps can accelerate the transition from experimental prototypes to robust, scalable systems, ensuring that Quantum Internet research remains at the forefront of technological innovation.

Limitations

While this study provides a comprehensive mapping of Quantum Internet research, several limitations must be acknowledged. The analysis was restricted to Scopus-indexed documents, which may omit relevant publications indexed elsewhere. The reliance on the query term “Quantum Internet” may not capture synonymous terms such as “quantum network” or “quantum internetwork,” potentially excluding some studies. Furthermore, the exclusion of review papers and certain document types, though intended to focus on original research outputs, may limit visibility of influential syntheses. These methodological choices may shape the observed trends and collaboration patterns. Nonetheless, the results highlight specific underexplored areas—such as limited integration of experimental hardware with network protocols and uneven regional participation—which provide tailored opportunities for future research and strategic investment.

CONCLUSIONS

The bibliometric analysis of Quantum Internet research highlights a rapidly growing field driven by interdisciplinary collaboration and technological innovation. Findings show strong global contributions, with the United States, China, and several European nations leading in output, while influential researchers and journals are shaping the theoretical and practical dimensions of the domain. Thematic analyses confirm that core areas such as entanglement distribution, quantum key distribution, and network architectures are well established, while emerging areas like blockchain integration, quantum IoT, and AI-driven security need further exploration. To strengthen this research landscape, it is recommended that future studies prioritize experimental validation and large-scale testbeds to bridge theory and practice, promote cross-disciplinary collaborations involving computing, engineering, and applied sciences, and develop standardization frameworks and policies to ensure secure and interoperable quantum networks. Addressing these areas will enhance scalability, reliability, and real-world applicability. Overall, the study provides a roadmap for stakeholders to identify critical gaps and opportunities, guiding investments and innovation. By aligning foundational research with application-driven needs, Quantum Internet can advance toward robust, secure, and globally accessible infrastructures.

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The authors declare that there is no conflict of interest.

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