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COMMENT

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Mapping the quantum computing landscape: growth, collaboration, and thematic convergence

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Abstract

Quantum computing has rapidly emerged as one of the fastest-growing research domains, driven by both technological breakthroughs and the promise of computational advantages over classical systems. This study presents a comprehensive bibliometric analysis of the global quantum computing literature from 1980 to 2025, comprising 31,662 publications indexed in Scopus and accumulating over 800,000 citations. Using advanced bibliometric techniques—including co-authorship mapping, keyword co-occurrence networks, co-citation analysis, and centrality measures—we characterize publication trends, institutional contributions, collaborative structures, and thematic evolution across the field. The results reveal exponential growth in output since 2015, led primarily by the United States, China, and Europe, with key institutions such as MIT, the Chinese Academy of Sciences, CNRS, and the University of Waterloo at the forefront. The intellectual structure exhibits a dual-core configuration, with foundational algorithmic work (e.g. Shor, Grover, Nielsen & Chuang) tightly connected to emerging NISQ-era applications such as quantum machine learning, cryptography, and hybrid algorithms. Keyword analysis reveals the progressive expansion from core quantum algorithms toward increasingly diverse applied domains in healthcare, finance, chemistry, energy, and climate modeling. Public funding bodies (e.g. NSFC, NSF, European Commission, DOE, DoD, MoST) and private-sector investment from major technology firms are jointly driving this translational acceleration. Together, these findings provide an integrated quantitative map of the field's evolution, offering valuable insight for future scientific policy, international collaboration, and strategic funding initiatives.

1 Introduction

Quantum computing represents one of the most disruptive frontiers in modern science and technology, rooted in the exploitation of quantum mechanical phenomena such as superposition, entanglement, and quantum interference to process information beyond the capabilities of classical systems. By operating on qubits rather than classical bits, quantum computers can explore exponentially larger state spaces, offering potential breakthroughs in cryptography, optimization, material design, drug discovery, and artificial intelligence [1].

The theoretical foundations of quantum computing were progressively established in the late 20th century (Fig. 1). In 1973, Charles H. Bennett introduced the concept of logical reversibility of computation, demonstrating that computation could, in principle, be performed without energy dissipation if information loss was avoided [2]. This result bridged computation with the laws of thermodynamics and initiated early discourse on the physical realizability of computation. Shortly thereafter, Yuri Manin (1980) postulated that quantum systems could serve as computational devices beyond the capabilities of classical machines, introducing the notion of quantum automata [3]. That same year, Paul Benioff constructed the first quantum mechanical model of the Turing machine, formalizing the compatibility of quantum mechanics with computational theory [4].

A major conceptual breakthrough occurred in 1982, when Richard P. Feynman argued that the efficient simulation of quantum systems is intractable for classical computers but could be naturally implemented on quantum hardware. This insight established quantum simulation as a primary motivation for developing quantum computers [4, 5]. Building on these developments, David Deutsch, in 1985, proposed the formal framework of the *universal quantum computer*, capable of simulating any physical process governed by quantum mechanics, thus generalizing the Church-Turing thesis to the quantum domain [6].

The 1990s saw the first concrete demonstrations of quantum computational advantage through algorithmic breakthroughs. The Deutsch–Jozsa algorithm (1992) offered the first clear example of exponential speedup for certain oracle problems [7]. In 1993, Daniel Simon introduced a problem exhibiting an exponential separation between classical and quantum computational complexity, directly inspiring Peter Shor's 1997 polynomial-time quantum algorithm for integer factorization and discrete logarithms [8]. Shor's algorithm had profound implications for modern cryptography, undermining the mathematical assumptions underpinning RSA and other widely deployed public-key encryption schemes [9]. In parallel, Grover's algorithm (1996) achieved quadratic speedup for unstructured search problems, further expanding the applicability of quantum computing [10].

Concurrently, major advances were made in quantum communication. In 1993, Charles H. Bennett and collaborators introduced the quantum teleportation protocol, demonstrating that an unknown quantum state could be faithfully transferred between distant locations through a combination of shared entanglement and classical communication [11]. This foundational result laid the groundwork for subsequent developments in quantum communication networks, quantum repeaters, and long-distance entanglement distribution.

These theoretical advances rapidly stimulated experimental efforts. By 1997, both quantum key distribution (QKD) over fiber-optic links (extending beyond 20 km) [12], and experimental demonstrations of quantum teleportation were achieved [13]. In the following years, small-scale quantum processors successfully implemented simplified versions of Grover's and Shor's algorithms: two-qubit systems at Berkeley (1998) [14], three-qubit implementations at IBM (1999) [15], and by 2000, Los Alamos National Laboratory achieved a seven-qubit liquid-state NMR realization of Shor's factoring algorithm—marking one of the first experimental demonstrations of algorithmic scalability in quantum computing [16, 17].

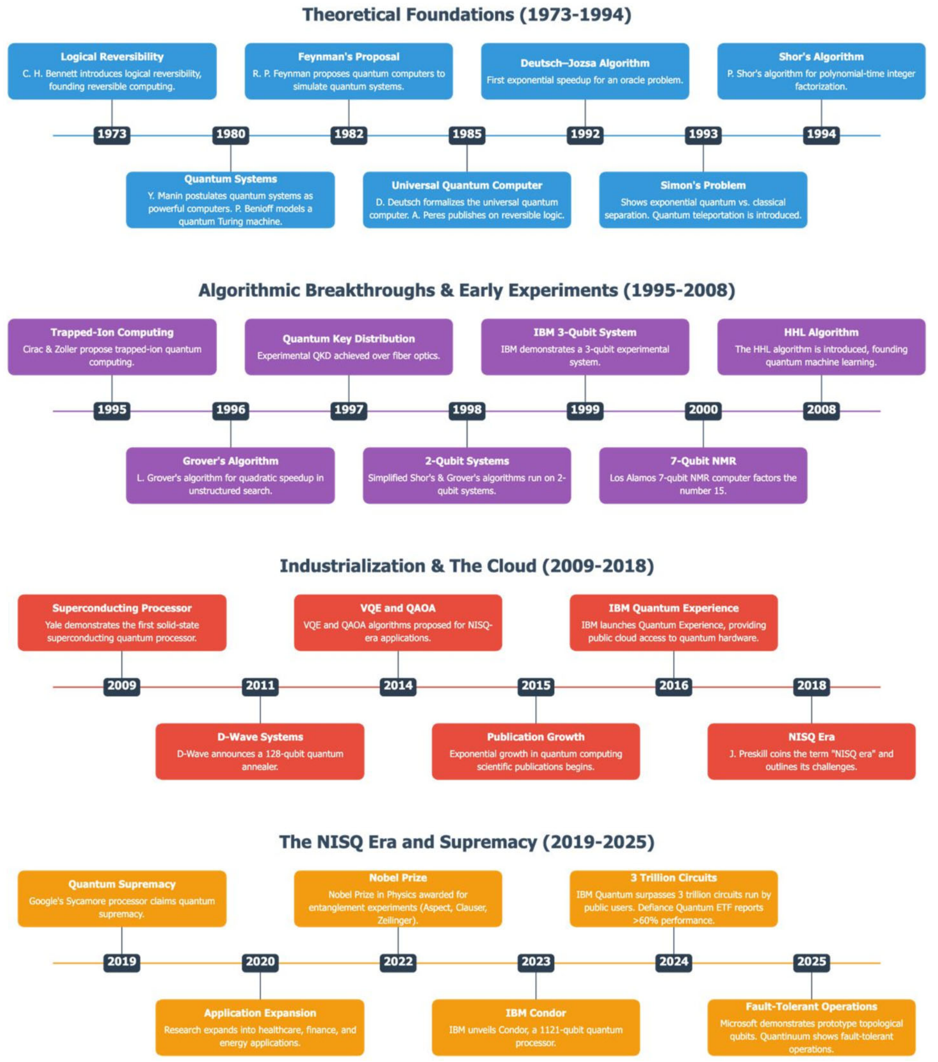


Figure 1 Timeline of quantum computing milestones (1973–2025). Major developments are grouped into four phases: theoretical foundations (reversible computing, universal quantum computation, early algorithms), algorithmic breakthroughs and experiments (quantum key distribution, Grover's and Shor's algorithms, small qubit systems), industrialization (hardware advances, cloud access, NISQ algorithms), and the NISQ era (quantum supremacy, expanding applications, large-scale hardware, and initial fault-tolerant operations)

Throughout the 2000s, steady progress was made in the physical realization of scalable quantum hardware. Ion-trap platforms, superconducting circuits, photonic architectures, and nuclear spin systems demonstrated increasing levels of coherence, gate fidelities, and multi-qubit control [16–20]. In parallel, the algorithmic frontier also advanced. In 2008, Harrow, Hassidim, and Lloyd introduced the HHL algorithm, providing an efficient quantum solution for systems of linear equations—a result that subsequently laid the groundwork for quantum machine learning protocols [21].

Entering the 2010s, the field experienced an unprecedented phase of industrialization and global investment. Yale demonstrated the first solid-state superconducting quantum processor in 2009 [22], while D-Wave Systems introduced a 128-qubit quantum annealer in 2011 [16, 17]. The development of hybrid quantum-classical algorithms further expanded the applicability of early quantum devices. The variational quantum eigensolver (VQE), proposed in 2014, together with amplitude amplification protocols, enabled the first practical applications in quantum chemistry, finance, and optimization on noisy intermediate-scale quantum (NISQ) devices [23].

In 2016, IBM democratized public access to quantum hardware through its IBM Quantum Experience platform, allowing global users to program and execute circuits on superconducting processors via cloud access [24]. A major milestone was reached in 2019 when Google's Sycamore processor demonstrated quantum computational supremacy by performing a random circuit sampling task in approximately 200 seconds, compared to an estimated 10,000 years on classical supercomputers [25].

Subsequent years have seen rapid technological advancements. In 2022, the Nobel Prize in Physics was awarded to Alain Aspect, John F. Clauser, and Anton Zeilinger for their pioneering experiments on quantum entanglement and the violation of Bell inequalities [26], providing definitive experimental confirmation of the nonlocal correlations that constitute a fundamental resource for quantum computation, communication, and cryptography [17]. In 2023, IBM unveiled its Condor processor, the first commercial gate-based quantum device surpassing 1000 qubits (1121 qubits) [17, 18]. In 2025, Microsoft introduced a prototype of a topological qubit architecture based on Majorana modes, offering intrinsic error protection [27]. Trapped-ion platforms such as Quantinuum have demonstrated fault-tolerant operations and certified quantum randomness on 50-qubit systems [28]. Throughout this period, companies such as IBM, Google, and Xanadu have offered cloud access to quantum systems—by early 2024, over 600,000 registered users had executed more than three trillion circuits and published nearly 2900 papers using Qiskit and IBM Quantum hardware—highlighting the explosive growth of quantum computing research [18, 29].

Despite these advances, quantum computing remains predominantly within the NISQ era [30], where devices are limited by noise, decoherence, and operational errors, typically operating with 50–100 qubits. Within these constraints, proof-of-concept demonstrations have been realized across multiple application domains, including molecular modeling for drug discovery [31–34], portfolio optimization in finance [32, 35], materials discovery for energy storage and catalysis [31], and early deployments of quantum key distribution for secure communications [35–38]. Researchers are actively exploring hybrid quantum-classical algorithms to extend computational capabilities in areas such as supply chain optimization, climate modeling, and logistics. The overarching objective remains the transition to fully fault-tolerant quantum computing (FTQC), which requires driving physical error rates below the threshold necessary for scalable error-corrected architectures. Achieving this milestone would unlock large-scale quantum systems capable of executing complex simulations, real-time optimizations, and industrial-grade quantum algorithms across multiple sectors [30].

The exponential growth of the field has recently prompted a surge in bibliometric analyses (2023–2025), yet a critical review identifies distinct limitations in their scope or currency. A significant portion of this recent literature, particularly the extensive body of work by Sood et al., concentrates on highly specific subdomains. These include analyses restricted to sustainable energy applications [39], materials science [40], physics-informed models [41], or quantum-inspired metaheuristics [42]. Other niche studies focus on post-quantum cryptography [43], climate science [44], quantum education [45], quantum research [46] or financial risk [47]. While valuable, these segmented analyses do not capture the holistic evolution of the quantum ecosystem. Conversely, broader landscape studies—including general reviews by Sood [20, 48] and others [19, 49–53]—often rely on datasets ending between 2020 and 2023, thereby missing the consolidation of the industrial phase observed in late 2024 and early 2025. Furthermore, while some works track technological trajectories via patents [54, 55], none systematically integrate bibliometric networks with funding sponsorship data. To address these gaps, the present study provides a comprehensive quantitative cartography of 31,662 publications from 1980 through May 2025, uniquely combining co-citation topologies, keyword evolution, and funding agency data to characterize the field's structural rigidity and industrial transition.

2 Materials and methods

2.1 Data source and retrieval strategy

The bibliometric dataset was constructed through a structured search conducted in the Scopus database. The search targeted publications related to the broad field of Quantum Computing, while systematically incorporating associated subdomains in quantum information, communication, cryptography, sensing, metrology, hardware, simulation, and software development to comprehensively capture the multidisciplinary landscape of quantum technologies. The time span covered publications from 1980 through May 11, 2025. No language restrictions were applied. Eligible document types included journal articles, reviews, book chapters, books, and conference proceedings.

To ensure high specificity and relevance, the search query was applied to the TITLE-ABS-KEY field using a complex Boolean strategy designed to retrieve publications directly addressing quantum computing and its technological ecosystem. A set of exclusion filters was implemented to eliminate documents primarily focused on unrelated materials science or condensed matter physics topics where "quantum" is often used in non-computational contexts. Specifically, documents referencing neutron scattering, polycrystalline materials, thin films, boundary conditions, or chemical reaction theories were excluded.

The search expression was organized into seven thematic modules representing: (1) quantum computing and quantum-mechanical computational models; (2) quantum information science, technology, and communication; (3) quantum cryptography and post-quantum cryptographic approaches; (4) quantum sensing and quantum control; (5) quantum metrology, tomography, clocks, gravimetry, and imaging; (6) quantum hardware systems and device architectures, and (7) quantum simulation, algorithms, and software frameworks. These thematic modules reflect the conceptual structure of the search design. The full Scopus query, including all Boolean operators, truncation rules, proximity operators, and field specifications exactly as implemented, is provided in the Supplementary Materials (Table S1). The complete search protocol, including scripts, search strings, and preprocessing pipelines, is publicly archived at: https://github.com/DanielCondeTorres/BIBLIOMETRIC.

All retrieved records were exported in CSV format, capturing full bibliographic metadata including author names, affiliations, document titles, abstracts, keywords, source titles, publication years, citation counts, and full reference lists.

2.2 Data cleaning and preprocessing

A multi-stage data cleaning process was applied to ensure dataset integrity and reproducibility. Duplicate records were identified and removed using a combination of DOI matching and title similarity algorithms. Affiliations and author names were standardized using Pandas (v2.2.3) [56] and thefuzz (1.2.2) [https://github.com/seatgeek/thefuzz] to handle variations (e.g., "MIT" vs. "Massachusetts Institute of Technology"). Records lacking essential bibliographic fields or exhibiting inconsistent metadata were systematically excluded. This procedure yielded a curated and validated corpus of quantum computing research publications across multiple subfields. The final cleaned dataset consisted of 31,662 documents, exported in CSV format with comprehensive metadata including author names, affiliations, titles, abstracts, keywords, sources, publication years, citations, and reference lists.

2.3 Bibliometric indicators, network construction, and mathematical framework

Bibliometric indicators were computed to quantify publication dynamics, productivity, and collaboration intensity within the quantum computing research landscape. Annual publication counts, mean total citations per article (MTC per article): $\frac{Total\ Citations\ (TC)}{Number\ of\ articles\ (N)}$ [57], and collaboration metrics—such as the Collaboration Index (CI, defined as the average number of authors per multi-authored paper): $CI = \frac{\sum_{j=1}^{k} j \cdot f_j}{N}$ and Collaboration Coefficient (CC, which adjusts for large teams: $CC = 1 - \frac{\sum_{j=1}^{k} \frac{1}{j} \cdot f_j}{N}$ where j is authors per paper, f_j is the number of papers with exactly j authors, N is the total number of papers and k is the maximum number of authors on any single paper [58])—were computed using the bibliometrix R package (v4.1) within its Biblioshiny interactive interface (accessed via R v4.4.3) [57]. CI measures average team size, while CC (bounded between 0 and 1) reflects collaboration intensity, with values above 0.5 indicating strong multi-authorship tendencies.

The construction of bibliometric networks employed the association strength measure as similarity index [59–61], enabling the generation of scientific maps that capture both static and dynamic structures within the research corpus [62]. Co-occurrence analysis was applied to identify the conceptual structure of the field; co-citation and bibliographic coupling analyses captured the intellectual structure; while co-authorship and affiliation-based studies reflected the social structure of scientific collaboration networks [59, 61].

Similarity was measured using the association strength index:

$$s_{ij} = \frac{c_{ij}}{\omega_i \omega_j}$$

where c_{ij} is the number of co-occurrences/co-citations of items i and j, and ω_i, ω_j are their total marginal frequencies. This normalization emphasizes relative rather than absolute relationships and improves cluster robustness [59–61].

For visualization and clustering, VOSviewer (v1.6.20) [63] was employed with the following parameters: minimum occurrences/citations = 5 for keywords/authors/documents (to filter noise while retaining core items); layout algorithm = attraction (strength = 2) and repulsion (strength = −1) for spatial optimization.

Clustering via Louvain modularity (resolution = 1.0), which partitions nodes into communities by maximizing modularity $Q = \frac{1}{2m} \sum_{i,j} [A'_{i,j} - \frac{k_i k_j}{2m}] \delta(c'_i, c'_j)$, where $A'_{i,j}$ is edge weight, k_i/k_j are degrees, m is total edges, and $\delta(c_i, c_j)$ is 1 if nodes i/j are in the same community [64]. This approach allows identification of thematic clusters (e.g., foundational vs. emerging subfields) without software dependency—networks can be rebuilt using adjacency matrices and standard graph algorithms, independent of specific software implementation.

For advanced network analyses, custom Python scripts were developed incorporating specialized libraries. NetworkX (v3.4.2) [65] was used to compute centrality measures and perform community detection; D-mercator (v1.0) [66] provided optimized graph layouts; pandas (v2.2.3) enabled efficient data manipulation; and matplotlib (v3.10.0) [67] facilitated the generation of visual analytics. A full mathematical description of the network metrics employed (e.g., Degree, Betweenness, PageRank), together with their interpretation, is provided in the Supplementary Materials (Table S2) [68, 69].

All data processing workflows, custom scripts, and analysis pipelines are openly accessible at: https://github.com/DanielCondeTorres/BIBLIOMETRIC.

3 Results and discussion

3.1 General descriptive statistics

The bibliometric dataset comprises 31,662 quantum computing publications authored by 66,171 unique contributors between 1980 and 2025. Of these, 3618 articles (11.4%) are single-authored, while multi-authored collaborations dominate with 28,044 papers (88.6%). The *Collaboration Index* (CI) [57]—defined as the average number of authors per paper—is 3.97, indicating that nearly four authors collaborate on each article on average. The *Collaboration Coefficient* (CC) [57, 70], which adjusts for the presence of large author teams to better reflect actual collaboration intensity, stands at 0.621. A CC value above 0.5 indicates a strong propensity toward multi-authorship and complex collaboration structures across the field.

The distribution of team sizes follows a long-tailed pattern (Fig. 2): teams of three authors are the most frequent (6887 articles; 21.8%), followed by two-author (6679; 21.1%) and four-author (5171; 16.3%) papers. Single-author works form a small minority (3618; 11.4%), while large collaborations ($\geq$10 authors) are less frequent but present. These patterns collectively reveal that small-to-medium-sized collaborative teams dominate quantum computing scholarship. A particularly notable case of large-scale collaboration involves a paper authored by 288 contributors describing the construction of the CUORE cryostat for neutrinoless double-beta decay searches, which informs the development of cryogenic systems applicable to quantum hardware [71]. While mathematically an outlier in the dataset, this document is analytically significant: it signals the intersection of quantum computing with "Big Science" infrastructure. It demonstrates that the development of stable cryogenic environments for superconducting qubits is transitioning from lab-scale experiments to massive engineering efforts comparable to high-energy physics collaborations. This shift in authorship patterns reflects the increasing complexity of the hardware layer, where progress requires large-scale, multidisciplinary consortia rather than isolated theoretical groups.

Language analysis shows an overwhelming dominance of English-language publications. Of the total documents, 31,149 (98.4%) are published in English. Chinese follows with 477 documents (1.5%), while all other languages combined (Russian, Portuguese, Japanese, Spanish, Turkish, Korean, German, etc.) represent less than 1% of the dataset,

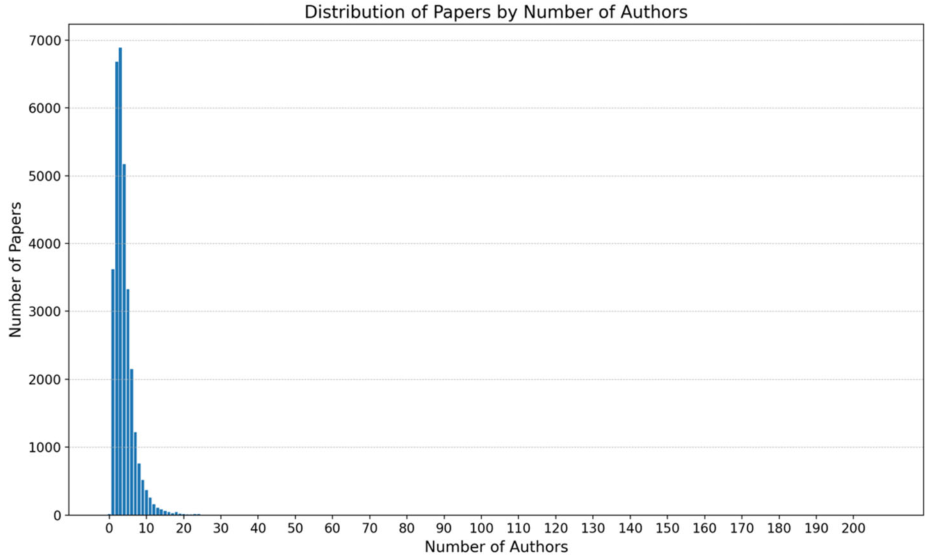


Figure 2 Distribution of quantum computing publications by team size. The histogram displays the number of articles (y-axis) as a function of the number of authors per publication (x-axis), illustrating a long-tailed collaboration pattern dominated by small- to medium-sized author teams

underscoring English's role as the lingua franca of quantum computing. This pattern carries implications beyond linguistic prevalence: despite China being the second-largest contributor to the field, the near-universal use of English indicates a strategic prioritization of global visibility and citation impact over domestic dissemination. Such linguistic convergence facilitates rapid cross-border knowledge transfer and reinforces the tight theoretical–experimental feedback loop that has become characteristic of the US–China–Europe research axis.

With respect to document types (Fig. 3A), journal articles account for 63.2% of all publications, conference papers for 31.6%, and reviews, book chapters, and books for the remaining small share. The subject areas (Fig. 3B) are primarily distributed across Physics and Astronomy (30.3%) and Computer Science (24.5%), together accounting for more than half of the dataset. This distribution reflects the dominant role of exact and computational sciences in the development of quantum computing research.

Publication venues also exhibit a strong concentration across a limited set of high-impact journals. Table 1 summarizes the top ten sources by publication count, together with their respective impact quartile rankings. The five Physical Review journals (Physical Review A - Atomic, Molecular and Optical Physics, Physical Review A, Physical Review Letters, Physical Review Research, and Physical Review B) dominate the Q1 category, reflecting their central role in disseminating foundational quantum physics research. Quantum Information Processing and Lecture Notes in Computer Science appear in Q2, specializing in quantum algorithms, information processing, and computational methods. Proceedings of SPIE has no formal quartile due to its classification as conference proceedings, while IEEE Access secures a Q1 ranking, underscoring the interdisciplinary expansion of quantum computing into engineering and applied sciences.

Temporal trends in annual scientific production (Fig. 4) show modest growth until the early 2000s, followed by exponential expansion beginning around 2015, peaking in 2024.

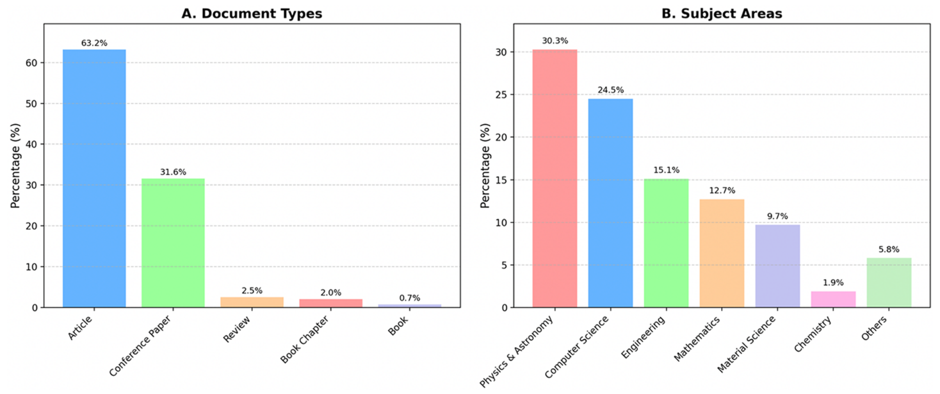


Figure 3 Composition of the quantum computing publication corpus. (**A**) Distribution of document types, showing that journal articles represent the majority of records (63.2%), followed by conference papers (31.6%), with reviews, book chapters, and books contributing marginal shares. (**B**) Disciplinary breakdown by subject area, where Physics & Astronomy (30.3%) and Computer Science (24.5%) dominate, alongside contributions from Engineering, Mathematics, Materials Science, Chemistry, and other fields

Table 1 Leading publication venues in quantum computing research (1980–2025). Top ten sources ranked by article count in the dataset, annotated with SCImago quartile [72] rankings. The five Physical Review journals (A, A - Atomic, Letters, Research, B) and New Journal of Physics fall into Q1, reflecting their leading role in disseminating high-impact physics research. Quantum Information Processing and Lecture Notes in Computer Science are classified as Q2, representing specialized niches in quantum algorithms and computational methods. Proceedings of SPIE is not assigned a quartile due to its classification as conference proceedings. IEEE Access appears as a multidisciplinary Q1-ranked journal spanning engineering and applied sciences

Rank	Sources	Articles	Quartile
1	PHYSICAL REVIEW A - ATOMIC MOLECULAR AND OPTICAL PHYSICS	1565	Q1
2	PHYSICAL REVIEW A	1479	Q1
3	PHYSICAL REVIEW LETTERS	1240	Q1
4	QUANTUM INFORMATION PROCESSING	1094	Q2
5	LECTURE NOTES IN COMPUTER SCIENCE (INCLUDING SUBSERIES LECTURE NOTES IN ARTIFICIAL INTELLIGENCE AND LECTURE NOTES IN BIOINFORMATICS)	992	Q2
6	PROCEEDINGS OF SPIE - THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING	860	N/A
7	NEW JOURNAL OF PHYSICS	547	Q1
8	PHYSICAL REVIEW RESEARCH	402	Q1
9	IEEE ACCESS	354	Q1
10	PHYSICAL REVIEW B	336	Q1

This growth reflects the field's increasing maturity and the entry into experimental and applied research stages. The mean total citations per article (green curve) display higher values for early publications due to their longer citation windows. Prominent citation peaks correspond to several landmark contributions, including Benioff's 1980 foundational work on quantum-mechanical Hamiltonian models for Turing machines (859 citations) [4], Deutsch's 1985 paper on universal quantum computation (3181 citations) [6], Peres's 1985 publication (678 citations) [73], and the mid-1990s breakthroughs by Shor (6684 citations) [9] and Grover (6114 citations) [10], which introduced transformational quantum algorithms. In more recent years, as expected, the average citation per paper gradually stabilizes due to limited time for accumulation. In contrast, the average yearly citations per cohort (red dashed line) remain relatively stable across the entire timeline, indicating consistent annual impact across publication years. The stable behavior of

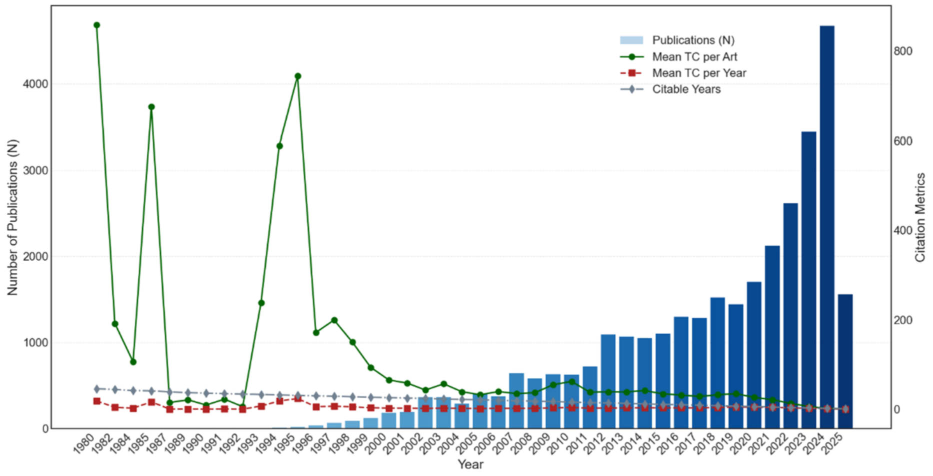


Figure 4 Temporal evolution of quantum computing publications and citation indicators (1980–2025). Blue bars show the annual number of publications. The green curve represents the mean total citations (TC) per article for each publication year, reflecting accumulated citations over time. The red dashed line displays the mean citations accrued per year across cohorts, while the gray curve indicates the number of citable years available for each publication cohort, confirming the consistent citation window applied across the dataset

the citable-year window (gray line) confirms the uniform application of citation windows across the dataset.

Cumulatively, the dataset has accrued 804,137 total citations, averaging 25.40 citations per paper. Of these, 24,671 publications (77.92%) have received at least one citation, with an average of 32.59 citations per cited article. Core bibliometric indices for the corpus yield h-index = 311, g-index = 569, i10-index = 11,378, i100-index = 1491, and i200-index = 593, indicating both depth and breadth of influence across the literature.

3.2 Global scientific production and collaboration patterns

The international landscape of quantum computing research reflects both scientific ambition and national strategic priorities, with a small number of countries accounting for the majority of global output. As shown in Fig. 5, the United States currently leads in total publication volume, contributing 27,092 articles, followed closely by China with 25,407. Germany ranks third (7893), while India emerges as a major contributor within the Asia-Pacific region (7305). This global distribution highlights the concentration of quantum computing research within a limited set of scientifically advanced and heavily invested national systems.

When assessed by corresponding author affiliation (Fig. 6), the distribution shows a slightly different pattern. China leads with 6695 articles, followed by the United States (6601), India (2348), and United Kingdom (1744). While China has a high volume of domestic articles (4552 SCP), its international collaboration rate (32%) remains comparable to leading European nations. A more striking contrast is found in India, which shows the lowest ratio of international partnership (approx. 21%). On the other hand, smaller contributors like Canada and Australia feature more balanced networks, with Multi-Country Publications (MCP) representing a much larger portion of their output compared to the top-ranking countries. This focus on corresponding author affiliation contrasts with the broader authorship-based output presented in Fig. 5, where the United States ranks as the

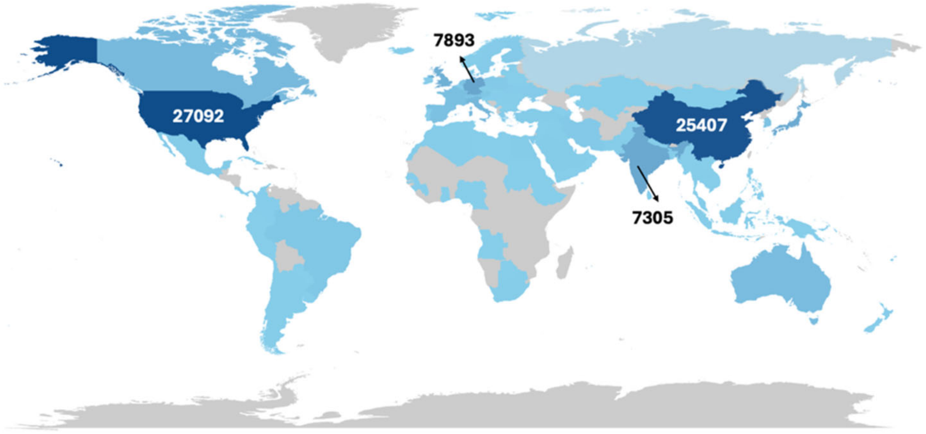


Figure 5 Global distribution of quantum computing publications by country. Color intensity reflects the number of Scopus-indexed publications (1980–2025), with darker shades indicating higher research output. The leading contributors are the United States (27,092 publications), China (25,407), Germany (7893), and India (7305), highlighting the concentration of quantum computing research within a few dominant national systems. Country counts refer to country–article instances (one entry per country involved in each publication), so a single article may be counted multiple times when it has authors from several countries

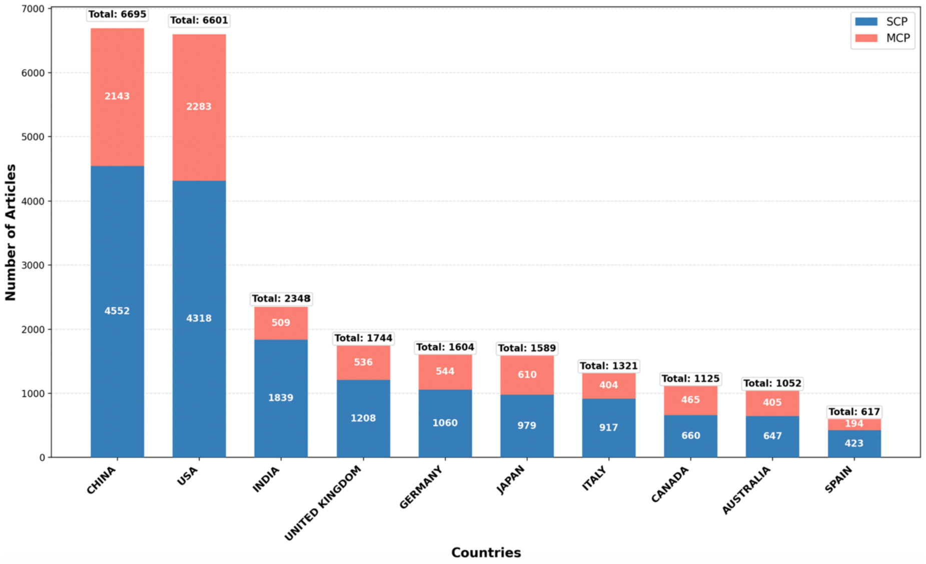


Figure 6 National research output based on corresponding author affiliations. For each country, bars indicate the number of single-country publications (SCP, blue: articles authored exclusively by domestic institutions) and multiple-country publications (MCP, red: articles involving at least one international co-author). Data reflect the degree of international collaboration across the top publishing countries in quantum computing

most represented affiliation overall. This discrepancy reflects differences in publication leadership patterns: while U.S. researchers frequently participate in international collaborations, they are proportionally less often designated as corresponding authors compared to their Chinese counterparts. Such authorship assignment patterns may reflect variations in institutional practices, funding structures, or national research policies regarding publication leadership.

Table 2 Most prolific institutions in quantum computing research (1980–2025), based on number of publications retrieved from Scopus

Institution	Documents by corresponding author
University of Science and Technology of China	1877
University of California	1040
CNRS (Centre National de la Recherche Scientifique)	759
Chinese Academy of Sciences	729
University of Waterloo	600
MIT (Massachusetts Institute of Technology)	593
University of Oxford	534
National University of Singapore	493

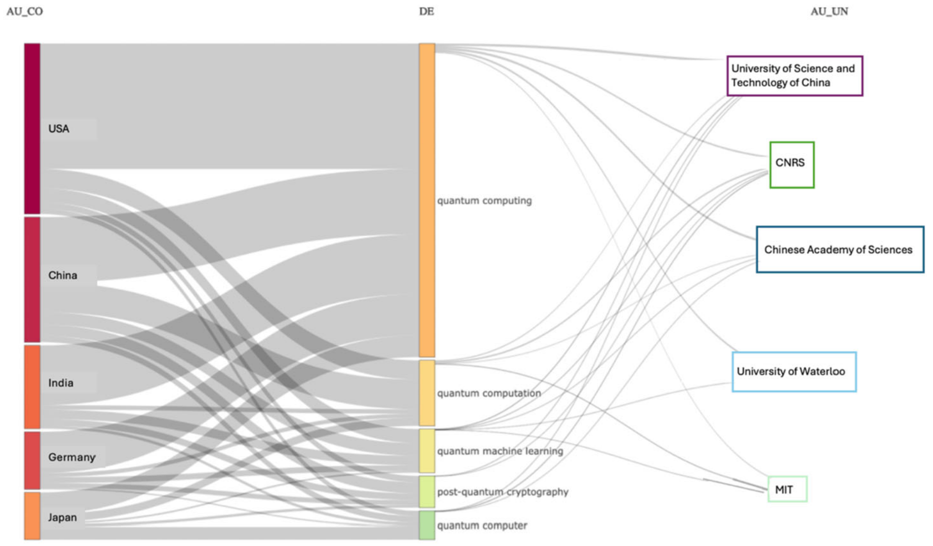


Figure 7 Three-field plot of quantum computing research (1980–2025), illustrating bibliometric linkages between author countries (AU_CO), research domains (DE), and affiliated universities (AU_UN). The width of connecting lines reflects the strength of association between countries, topics, and institutions

At the institutional level (Table 2), the University of Science and Technology of China emerges as the most prolific affiliation (1877 articles), reflecting its central role in China's national quantum research strategy. This is followed significantly by the University of California system (1040 documents). France's CNRS (759 publications) underscores its leadership within European research networks, while the Chinese Academy of Sciences (729) further illustrates the region's rapid institutional expansion. In North America, the University of Waterloo (600) and the Massachusetts Institute of Technology (593) represent leading centers of innovation, while the University of Oxford (534) continues to maintain a strong global presence. The National University of Singapore (493) exemplifies the rising prominence of Asia-Pacific institutions.

In addition to aggregate publication counts, the structural relationships between countries, research domains, and institutional affiliations are illustrated in Fig. 7. The three-field Sankey diagram maps these connections across author countries (AU_CO), research domains (DE), and affiliated universities (AU_UN). The United States, China, and India emerge as the leading national contributors, strongly connected to central themes such as "quantum computing", "quantum machine learning", and "post-quantum cryptography".

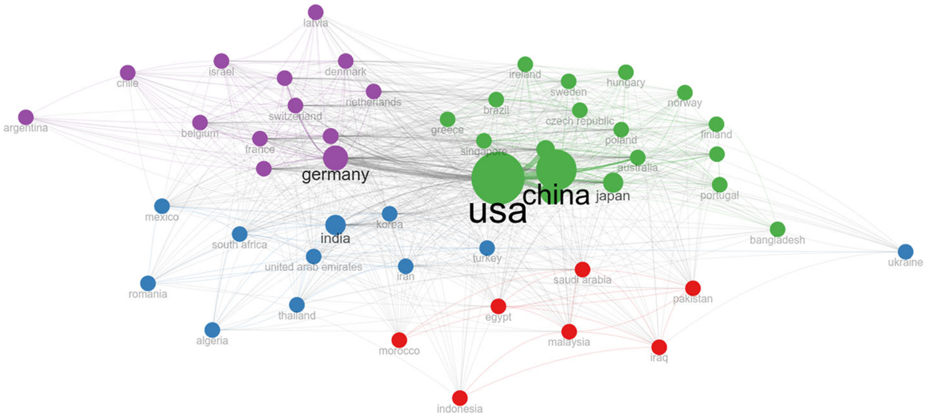


Figure 8 International collaboration network in quantum computing research (1980–2025). Nodes represent countries, sized proportionally to their publication output, while edges indicate co-authorship linkages. Node colors represent communities detected via the Louvain modularity algorithm. Countries sharing the same color exhibit a higher density of collaboration with each other than with the rest of the network, highlighting the existence of tightly-knit strategic research alliances underlying the global structure. The USA–China axis dominates the network core, with dense intra-European, Asia-Pacific, and regional subnetworks also visible. The network illustrates the highly interconnected global structure of quantum computing collaborations

The University of Science and Technology of China, CNRS, the University of Waterloo, the Chinese Academy of Sciences, and MIT appear as highly productive institutions across these domains, reflecting their central role in quantum computing research ecosystems.

Country-level collaboration networks (Fig. 8) reveal the structural properties of international partnerships, with the U.S.–China bilateral relationship at the network core, complemented by dense intra-European and Asia-Pacific subnetworks. Centrality metrics further quantify each country's role within the global collaboration system. *Degree centrality*, which reflects the number of direct collaborations, is highest for the United States (0.7453), suggesting partnerships with nearly three-quarters of all countries in the dataset. India (0.6981), the United Kingdom (0.6792), Spain (0.6321), and Germany (0.6321) also maintain extensive bilateral collaborations. *Betweenness centrality* highlights countries that act as intermediaries facilitating indirect connections between others; here, India leads (0.1135), followed by the United States (0.0854) and Germany (0.0838). *Eigenvector centrality*, which accounts for both the quantity and influence of collaborators, ranks the United States highest (0.1982), followed by the United Kingdom (0.1916), India (0.1883), Spain (0.1831), and Germany (0.1822), indicating their integration within the core leadership of the global quantum computing network.

Beyond individual country centralities, several global-level metrics further characterize the overall structure of international collaborations in quantum computing. The network exhibits a *density* of 0.2174, indicating that approximately 21.7% of all possible country-to-country collaborations are realized, reflecting a moderately interconnected global system. The *average path length* is 1.9328, meaning that any two countries are, on average, separated by fewer than two collaborative steps—highlighting the network's efficiency in disseminating information. A high *clustering coefficient* of 0.7349 confirms a strong tendency for countries to form tightly-knit groups, often reflecting regional or thematic collaboration clusters. The *small-world sigma value* of 3.2124 further supports the presence of small-world properties, characterized by a combination of local cohesion and global connectivity that facilitates rapid knowledge diffusion across the field. Notably, attempts to fit a *power-law distribution* to the degree sequence did not yield a reliable exponent, indicating that the network deviates from a purely scale-free topology. Instead, its structure appears shaped by a combination of regional alliances, institutional partnerships, and policy-driven collaborations, rather than by preferential attachment alone.

This structural organization is visually reinforced by the community detection analysis shown in Fig. 8. The modularity optimization groups countries into distinct clusters (node colors) based on the density of their bilateral ties rather than strict geographical proximity. This reveals that the global quantum computing network is organized into strategic collaborative blocs, where membership is defined by the frequency of joint research output. These communities illustrate how scientific alliances in this high-tech domain often transcend continental boundaries, linking major research hubs with specific international partners based on shared funding initiatives or historical research ties.

Altogether, these properties portray a highly interconnected, efficient, and balanced global research network, where both major hubs and peripheral contributors participate in sustaining the cohesion and resilience of international quantum computing collaborations.

3.3 Citation impact and highly cited contributions

While research output and collaboration patterns capture the structural dimensions of global quantum computing research, citation analysis provides a complementary perspective by identifying those contributions that have exerted the most significant influence on the field's intellectual development and visibility. Citation-based indicators reflect the cumulative recognition of scientific work, its adoption by the research community, and its role in shaping evolving research agendas. The citation analysis developed here integrates document-level citation performance, intra-dataset citation flows, reference co-citation frequencies, author-level profiles, intellectual network topology, and country-level patterns, providing a multidimensional perspective on the field's structure and evolution.

The first level of analysis evaluates the global citation performance of the documents included in the dataset, as indexed by Scopus. Table 3 summarizes the total number of citations each document has received, regardless of the source of those citations. This indicator provides a measure of external visibility, capturing how publications included in the dataset have been cited by the broader global scientific community. Several canonical contributions occupy central positions in the citation hierarchy. The review Colloquium: Topological Insulators by Hasan and Kane (16,746 citations) [74] established a foundational understanding of topological insulators—materials exhibiting surface conduction protected by topological order—which has opened new avenues for quantum information science and quantum hardware platforms. Peter Shor's seminal works introduced quantum algorithms capable of breaking widely used classical cryptographic schemes, laying the foundation for the computational superiority of quantum systems. His publications Algorithms for Quantum Computation: Discrete Logarithms and Factoring (6649 citations) [75] and Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer (5566 citations) [9] remain highly cited references in both theoretical and applied contexts. Lov Grover's A Fast Quantum Mechanical Algorithm for Database Search (6614 citations) [10] proposed a quadratic speedup for unstructured search problems, marking a milestone in quantum algorithmics. Alexei Kitaev's

Table 3 Total Scopus citation counts for documents included in the analyzed dataset (1980–2025). Total number of citations indexed by Scopus for each document included in the dataset, regardless of citing source

Title	Total Scopus citations
Colloquium: Topological insulators [74]	16,746
Algorithms for quantum computation: Discrete logarithms and factoring [75]	6649
A fast quantum mechanical algorithm for database search* [10]	6614
Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer [9]	5566
Fault-tolerant quantum computation by anyons [76]	5301
Quantum computing in the NISQ era and beyond [30]	5032

Fault-Tolerant Quantum Computation by Anyons (5301 citations) [76] introduced topological quantum computation, utilizing anyonic quasiparticles to achieve intrinsic error resilience and fault tolerance. Finally, John Preskill's Quantum Computing in the NISQ Era and Beyond (5032 citations) [30] articulated the challenges and opportunities associated with NISQ devices, shaping much of the field's contemporary research agenda.

Critically, this citation hierarchy reveals the fundamental tension defining the current state of the field. The sustained dominance of Shor's and Grover's papers (1990s) alongside Preskill's "NISQ" definition (2018) illustrates a technological gap: the community possesses powerful theoretical proofs of quantum advantage but is operationally constrained by noisy hardware. The bibliometric data does not merely reflect historical importance but points to a specific research bottleneck. The absence of mid-2000s papers in the top tier, compared to the surge of recent hybrid algorithm papers (VQE, QAOA), indicates that the research front has shifted from finding new theoretical speedups to engineering "workarounds" that can function within the error budgets of current devices. Thus, the citation landscape maps a transition from pure algorithmic discovery to pragmatic error mitigation.

Within this document-level citation analysis, recent highly cited publications illustrate emerging research frontiers that have attracted substantial attention in the period 2020–2025. The review by McArdle et al. on quantum computational chemistry [77] has accrued approximately 250 citations, highlighting quantum chemistry as a leading application for NISQ devices. Gidney and Ekerå's work [78] on resource-optimized quantum cryptanalysis reached ∼116 citations, proposing significant reductions in hardware requirements for factoring large RSA integers. Cerezo et al. [79] analyzed barren plateaus in variational circuits (∼115 citations), identifying how carefully chosen cost functions mitigate gradient vanishing in variational quantum algorithms. Bharti et al. [80] offered a comprehensive review of NISQ algorithms (∼82 citations), consolidating frameworks such as VQE, QAOA, quantum simulation, and benchmarking protocols. The Qiskit software stack also registered high citation activity, with the community paper stack [81] and architecture description (∼36 citations, 2024) [82] documenting its scalable open-source framework. Finally, the experimental report by the PsiQuantum team [83] on manufacturable photonic quantum computing platforms, though very recent (∼5 citations), signals important developments in scalable photonic hardware integration.

While total global citation counts capture external visibility, intra-dataset citation analysis provides insight into the internal citation dynamics operating within the quantum computing research community itself. Table 4 reports the number of times each docu-

Table 4 Intra-dataset citation counts for documents included in the dataset (1980–2025). Number of times each document is cited by other documents within the analyzed dataset

Title	Intra-dataset citations
A fast quantum mechanical algorithm for database search* [10]	1562
Algorithms for quantum computation: Discrete logarithms and factoring [75]	1489
Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer [9]	1007
Variational quantum algorithms [84]	420
Quantum Complexity Theory [85]	355

Table 5 Most frequently cited references across dataset bibliographies (1980–2025). Frequency with which each reference appears in the bibliographies of documents included in the dataset. References may include works external to the dataset

Title	Citation frequency
NIELSEN M.A., CHUANG I.L., QUANTUM COMPUTATION AND QUANTUM INFORMATION [86]	2748
PRESKILL J., QUANTUM COMPUTING IN THE NISQ ERA AND BEYOND, QUANTUM [30]	1973
A fast quantum mechanical algorithm for database search* [10]	1562
Algorithms for quantum computation: Discrete logarithms and factoring [75]	1489
Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer [9]	1007

ment in the dataset has been cited by other documents also included in the dataset, representing internal intellectual centrality. The intra-dataset citation structure largely mirrors global patterns but reveals some divergence in local citation dynamics. Grover's quantum search algorithm [10] (1562 intra-dataset citations) and Shor's discrete logarithm [75] and factorization algorithms [9] (1489 and 1007 intra-dataset citations, respectively) remain the most central. Recent developments, such as Variational Quantum Algorithms [84] (420 intra-dataset citations) and Quantum Complexity Theory [85] (355 intra-dataset citations), also demonstrate growing prominence in internal citation flows, reflecting their increasing importance in contemporary quantum computing research.

In addition to analyzing citation flows between documents included in the dataset, cited reference analysis identifies the intellectual foundations most frequently referenced across the bibliographies of the dataset corpus. Table 5 reports the frequency with which specific references appear, including both works that belong to the dataset and external works. As expected, Nielsen and Chuang's textbook *Quantum Computation and Quantum Information* (2000) [86] dominates, being cited 2748 times, and remains the central pedagogical and theoretical source for the field. Preskill's *Quantum Computing in the NISQ Era and Beyond* [30] is referenced 1973 times, while Grover's [10] and Shor's [9, 75] algorithmic papers also appear prominently. The alignment observed between intra-dataset citations (Table 4) and cited reference frequencies (Table 5) for shared documents reinforces the robustness of the dataset's internal citation structure.

At the author level, citation impact offers a further perspective on individual scholarly contributions. Figure 9 presents a comparative profile of authors across publication output, H-Index, and total citations. In terms of productivity (Fig. 9A), Robert Wille leads with 158 documents, followed by Guang-Can Guo (116), Frederic T. Chong (94), Franco Nori (74), Akira Furusawa (66), Keisuke Fujii (64), Rolf Drechsler (62), Jian-Wei Pan (60), Daniel A. Lidar (56), and Kae Nemoto (54). In H-Index (Fig. 9B), Franco Nori ranks first (36), followed by Jian-Wei Pan (33), Daniel A. Lidar (32), Robert Wille (29), and Guang-Can Guo

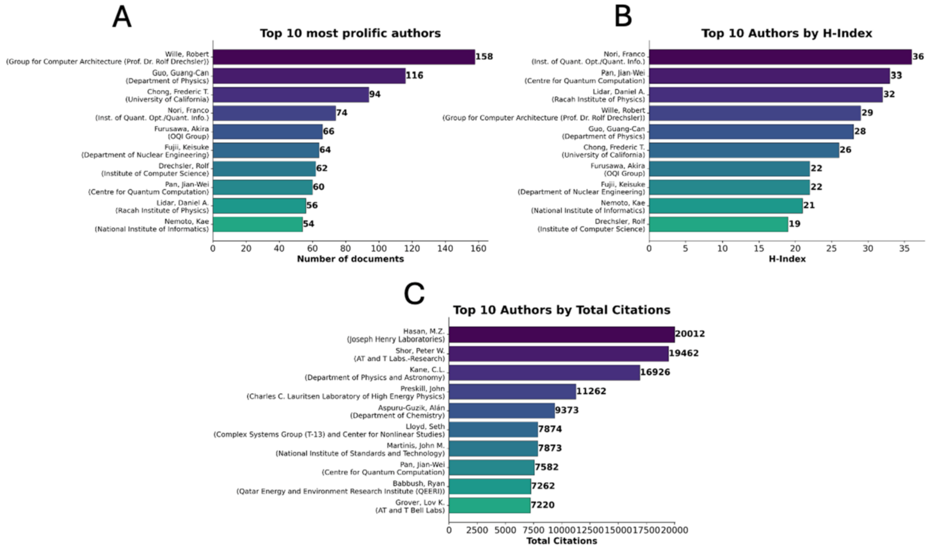


Figure 9 Author-level citation impact in quantum computing based on the analyzed dataset (1980–2025). (**A**) total publication output (number of documents in the dataset), (**B**) H-index calculated from dataset citations, and (**C**) total citation count accumulated within the dataset. The combined metrics reflect complementary aspects of scholarly influence, capturing both productivity and citation impact

(28). In total citation counts (Fig. 9C), M. Z. Hasan leads with over 20,000 citations, followed by Peter W. Shor (≈19,500), C. L. Kane (∼16,900), John Preskill (11,262), and Alán Aspuru-Guzik (9373). Juan Ignacio Cirac, although represented by only 43 documents within this dataset, holds a foundational role in quantum computing, with over 651 peer-reviewed articles, more than 75,000 citations, and an H-Index of 138 according to Web of Science [87], placing him among the top 3% of scholars globally [88]. His pioneering work with Peter Zoller in ion-trap quantum computing and optical lattice simulations has had lasting experimental and theoretical impact [89]. In recognition of his transformative work, Cirac has received numerous honors, including the 2006 Prince of Asturias Award in Technical and Scientific Research and the 2013 Wolf Prize in Physics [88]. Together, these metrics and accolades solidify Juan Ignacio Cirac's status as an indispensable figure whose breadth of publication and depth of citation impact exemplify the highest echelons of influence in quantum computing.

The co-citation network analysis, presented in Fig. 10, provides a structural validation of the field's historical development. Consistent with the field's trajectory, the topology reveals a distinct bimodal architecture: a red cluster centered around foundational works—Shor (1994) [9, 75], Grover (1996) [10], Nielsen & Chuang (2000) [86]—which form the theoretical backbone of quantum computing; and a blue cluster reflecting recent advances in NISQ algorithms, variational methods, and quantum machine learning (2010–2024). While this separation between theory and application is conceptually anticipated, the network metrics formally quantify the extent of their integration. Rather than evolving into isolated silos, the two clusters remain tightly coupled through high-centrality "bridge" nodes, indicating that modern industrial applications remain structurally dependent on classical theoretical frameworks.

Within this co-citation topology, three works emerge as structurally significant nodes. Farhi et al. (2014) [90] introduced the Quantum Approximate Optimization Algorithm

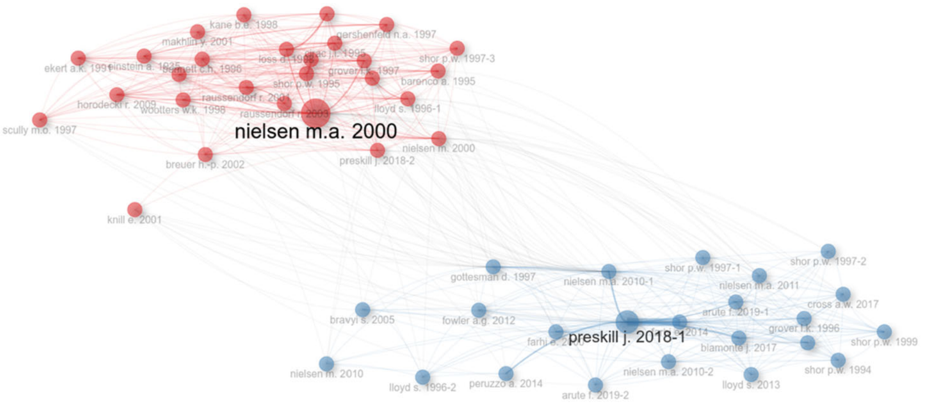


Figure 10 Co-citation network of the 100 most cited publications in quantum computing (1980–2025). Node size is proportional to total citation count; edge opacity reflects co-citation strength between pairs of documents. Clusters were identified using Louvain community detection and are color-coded: red cluster (foundational theoretical works, mid-1990s canonical contributions), and blue cluster (NISQ-era applied research, 2010–2025). Bridge publications connecting both clusters are positioned centrally. The network illustrates the dual-core intellectual structure of quantum computing, highlighting the interaction between classical algorithmic foundations and emerging near-term applications

(QAOA), serving as a bridge across multiple subfields (betweenness centrality = 32.331; closeness centrality = 0.008; PageRank = 0.049). Nielsen and Chuang's textbook [86] acts as the most integrative reference (betweenness centrality = 563.615; closeness centrality = 0.011; PageRank = 0.028), while Gottesman (1997) [91] on stabilizer codes contributes foundational principles for fault-tolerant computation (betweenness centrality = 158.265; closeness centrality = 0.009; PageRank = 0.015). Collectively, these nodes illustrate how both theoretical and applied subdomains are interconnected through a relatively stable intellectual infrastructure.

Finally, country-level citation performance based on the dataset reveals substantial variation across national research systems (Table 6). The United States dominates in absolute citation volume (138,916 citations), reflecting its extensive research capacity and global collaborative reach. However, its average citations per paper (44.0) are exceeded by smaller research systems such as Austria (50.7) and South Africa (48.4), whose high per-paper impact likely stems from intensive international collaborations (higher MCP ratios, Fig. 6) that enhance visibility across cross-border networks. China ranks second in total citations (53,454) but shows a markedly lower average citations per article (11.9), consistent with its emphasis on domestic output (high SCP ratio, Fig. 6) and somewhat more limited integration into global collaboration networks—a pattern often shaped by national publication policies that prioritize output volume. European countries such as the United Kingdom (38.3) and Switzerland (41.1) exhibit balanced profiles, combining thematic specialization in high-impact areas (e.g., life sciences, climate science, materials) with robust international partnerships. Canada (32.8) and Germany (21.5) occupy intermediate positions, potentially reflecting broader disciplinary diversity or hybrid collaboration models. Collectively, these patterns underscore that citation-based impact is not simply driven by output volume but emerges from the interplay between research intensity, thematic focus, and global scientific integration.

Table 6 Comparative ranking of countries by total citations and by average citations per article based on documents included in the dataset (1980–2025). Total citations and average citations per publication calculated from documents included in the dataset. Complementary metrics are indicated in parentheses

Rank (Total Citations)	Country	Total Citations (Avg. Citations)
1	USA	138,916 (44.0)
2	China	53,454 (11.9)
3	United Kingdom	31,643 (38.3)
4	Germany	20,775 (21.5)
5	Canada	17,828 (32.8)

Rank (Avg. Citations)	Country	Avg. Citations (Total Citations)
1	Austria	50.7 (8220)
2	South Africa	48.4 (1499)
3	USA	44.0 (138,916)
4	Switzerland	41.1 (8841)
5		

3.4 Thematic structure and conceptual evolution

The conceptual landscape of quantum computing research exhibits a structured interplay between foundational algorithmic principles and expanding applied domains. Analysis of keyword frequency, co-occurrence relationships, thematic positioning, and temporal trends provides a data-driven representation of how the field has developed across multiple dimensions (Figs. 11–14).

Keyword frequency analysis (Fig. 11A) indicates that “quantum computing” is the most frequently occurring term, followed by “quantum computation”, “quantum machine learning”, and “post-quantum cryptography”. These terms reflect the central research domains within the corpus, combining foundational algorithmic development, emerging computational paradigms, and security-oriented topics.

The co-occurrence network (Fig. 11B) reveals the internal relational structure among research topics. Thematic clusters emerge, delineating subdomains such as “quantum algorithms” (blue), “quantum machine learning” (yellow), and “post-quantum cryptography” (green). The central role of quantum computing is confirmed both visually and quantitatively. Centrality metrics further characterize this structure: quantum computing exhibits the highest betweenness (485.800), closeness (0.020), and PageRank (0.182), confirming its function as the primary hub. Quantum computation (betweenness 43.298, closeness 0.019, PageRank 0.046), quantum machine learning (betweenness 6.832, closeness 0.015, PageRank 0.040), and quantum cryptography (betweenness 6.926, closeness 0.017, PageRank 0.030) reflect secondary but growing thematic centers. Temporal layering of topics is visualized in Fig. 11C, where node color reflects average publication year. Recent growth is evident in “quantum machine learning”, “noise mitigation”, and “post-quantum cryptography”, while established areas such as “quantum error correction” and “hardware” maintain sustained prominence across the entire period analyzed.

The heatmap in Fig. 12 provides a quantitative matrix of keyword co-occurrence frequencies across eight core terms: “quantum computing”, “quantum computation”, “quantum machine learning”, “post-quantum cryptography”, “quantum computer”, “quantum information”, “entanglement”, and “quantum algorithms”. High-frequency co-occurrences include the pair “quantum computing” and “quantum machine learning” (263 documents), as well as “quantum computing” and “quantum algorithms” (157 documents), confirming strong thematic linkages between emerging algorithmic approaches and foundational

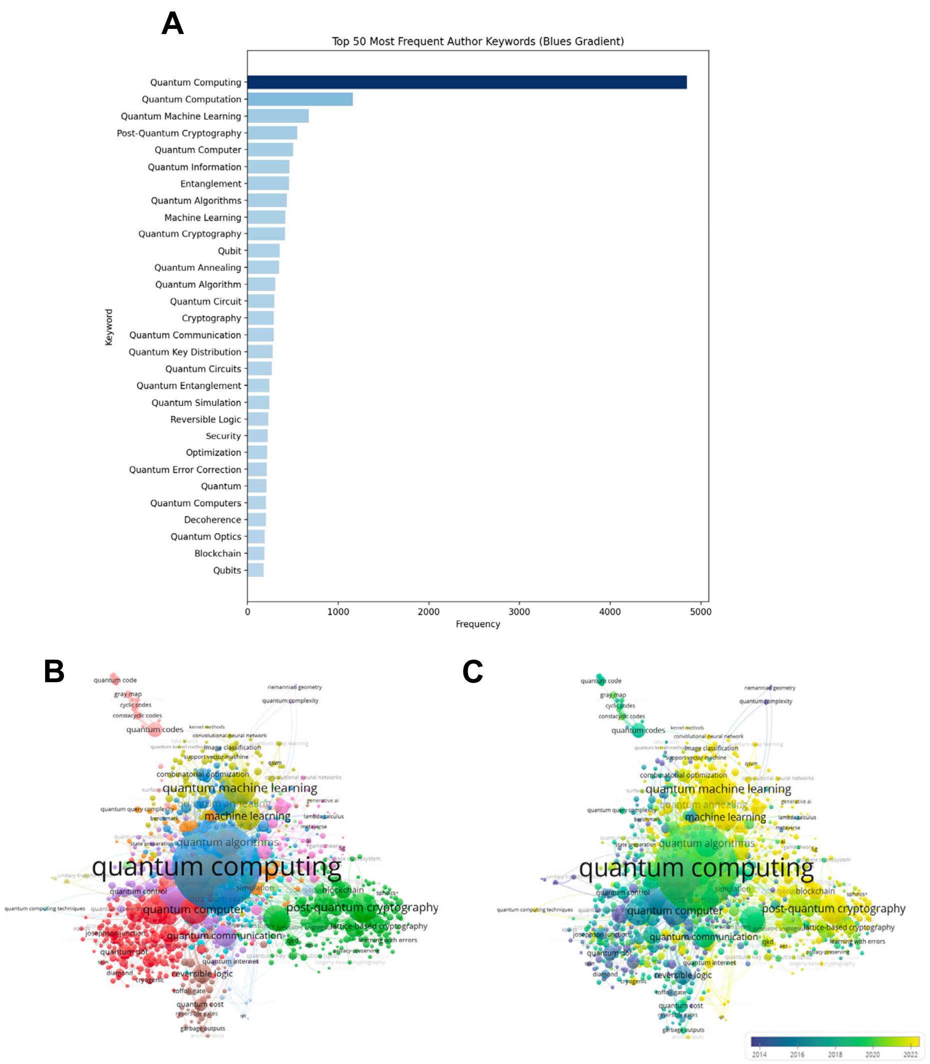
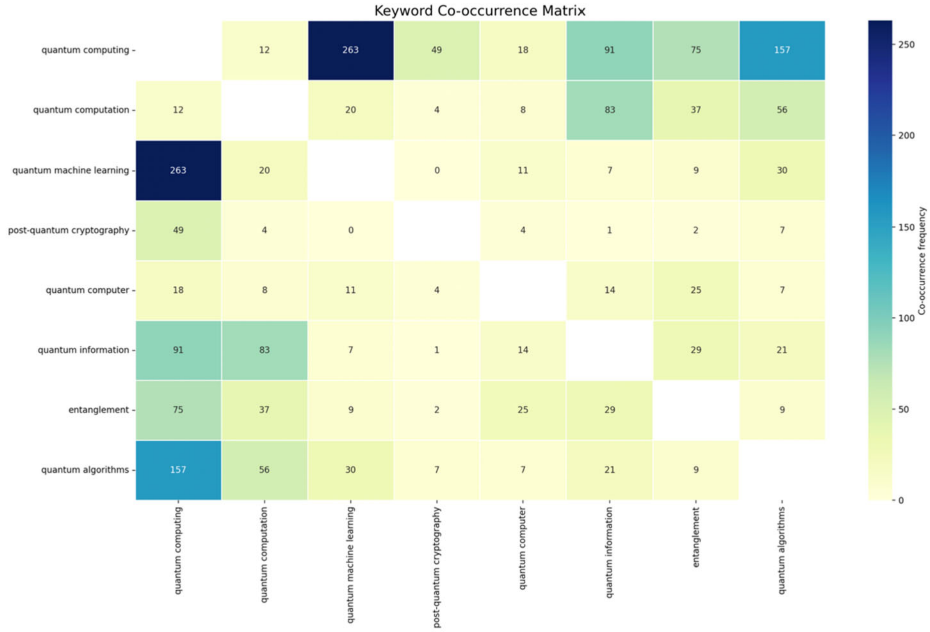


Figure 11 Keyword structure of quantum computing research (1980–2025). (**A**) Bar chart displaying the top 20 most frequent keywords across the dataset. "Quantum computing" is the most frequent term, followed by "quantum computation," "quantum machine learning," and "post-quantum cryptography." (**B**) Keyword co-occurrence network colored by thematic clusters: quantum algorithms (blue), quantum machine learning (yellow), and post-quantum cryptography (green); node size reflects keyword frequency and edge thickness indicates co-occurrence strength. (**C**) Co-occurrence network colored by average publication year (blue = earlier; yellow = more recent), illustrating the temporal evolution of research trends. Recent growth is observed in quantum machine learning, noise mitigation, and post-quantum cryptography, while core topics such as quantum error correction and hardware remain consistently prominent throughout the period. Clusters were detected using the Louvain algorithm as implemented in VOSviewer [63]

computational paradigms. Conversely, low co-occurrence values are observed for "post-quantum cryptography" with other concepts (e.g., only 4 co-occurrences with "quantum computation"), suggesting distinct topical boundaries between cryptographic security frameworks and core quantum algorithmic research. These patterns delineate both convergent research cores and areas of thematic differentiation within the broader quantum computing literature.

The thematic map (Fig. 13) organizes research topics along the centrality-density plane, dividing them into four conceptual quadrants. *Motor Themes* include "quantum com-



	quantum computing	quantum computation	quantum machine learning	post-quantum cryptography	quantum computer	quantum information	entanglement	quantum algorithms
quantum computing		12	263	49	18	91	75	157
quantum computation	12		20	4	8	83	37	56
quantum machine learning	263	20		0	11	7	9	30
post-quantum cryptography	49	4	0		4	1	2	7
quantum computer	18	8	11	4		14	25	7
quantum information	91	83	7	1	14		29	21
entanglement	75	37	9	2	25	29		9
quantum algorithms	157	56	30	7	7	21	9	

Figure 12 Heatmap of keyword co-occurrence frequencies in quantum computing research (1980–2025). Matrix showing co-occurrence frequencies across eight key terms: “quantum computing”, “quantum computation”, “quantum machine learning”, “post-quantum cryptography”, “quantum computer”, “quantum information”, “entanglement”, and “quantum algorithms”. Cell values represent the number of documents in which each keyword pair appears together; darker shades indicate higher co-occurrence frequencies, highlighting both strong conceptual linkages (e.g., “quantum computing” with “quantum machine learning” and “quantum algorithms”) and weaker thematic overlaps (e.g., “post-quantum cryptography” with “quantum computation”)

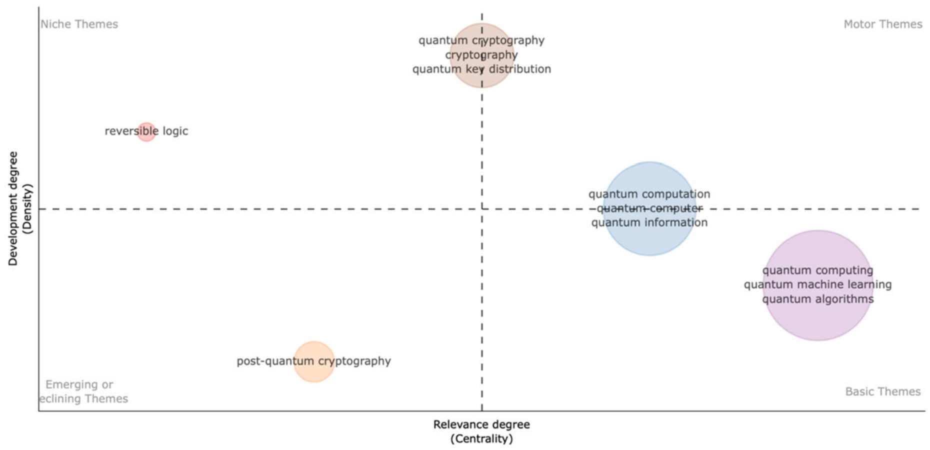


Figure 13 Thematic map of quantum computing research (1980–2025). Bubble size reflects keyword frequency; the horizontal axis represents centrality (relevance within the overall network), while the vertical axis indicates density (internal development of each theme) [57]. Topics are positioned into four standard quadrants: *Motor Themes* (high centrality and density), *Basic Themes* (high centrality, lower density), *Niche Themes* (low centrality, high density), and *Emerging or Declining Themes* (low centrality and density)

putation”, “quantum computer”, and “quantum information”, reflecting highly developed and central research domains. *Basic Themes* encompass “quantum computing”, “quantum machine learning”, and “quantum algorithms”, which are broadly relevant but still under-

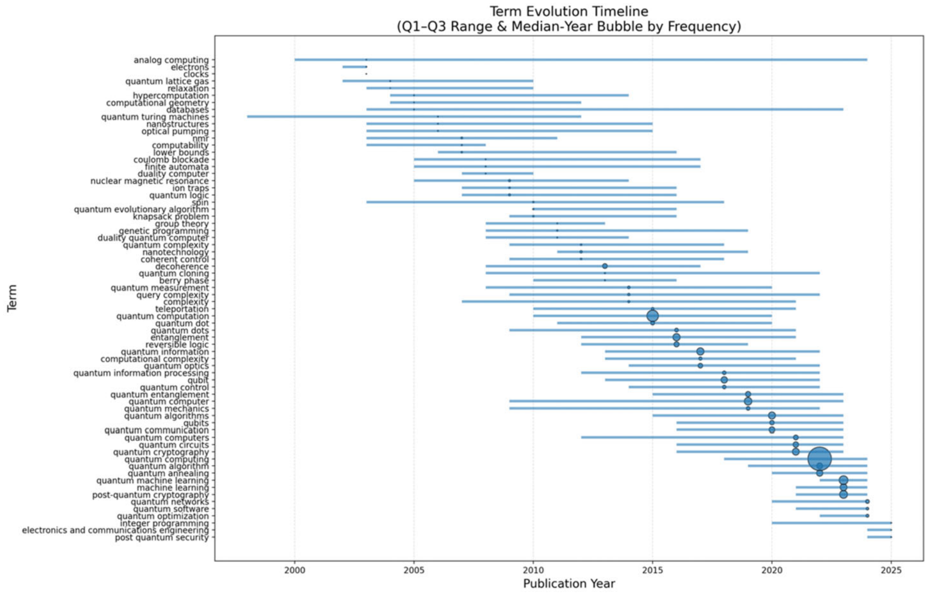


Figure 14 Temporal evolution of research terms in quantum computing (1980–2025)

going thematic consolidation. *Niche Themes* consist of "quantum cryptography", "cryptography", "quantum key distribution", and "reversible logic", representing specialized and well-developed but less centrally integrated areas. Finally, "post-quantum cryptography" is classified as an *Emerging or Declining Theme*, indicating growing but still underdeveloped research activity. This distribution highlights how core algorithmic and computational foundations remain central, while new applied domains continue to diversify and evolve.

Temporal evolution analysis (Fig. 14) characterizes the chronological dynamics of 45 key research terms within the quantum computing literature between 1980 and 2025. For each term, the distribution of publication years is represented by its interquartile range (Q1 to Q3), with the median year marked by a circle whose size is proportional to the total frequency of publications. This visualization captures both the historical onset and the ongoing relevance of each topic. Foundational terms such as "analog computing" and "electrons" exhibit wide temporal spans starting in the 1980s, reflecting their long-standing presence. In contrast, recently emerging topics such as "quantum machine learning" and "post-quantum security" concentrate around 2020, with later medians and large node sizes indicating their current growth and rising prominence. This temporal mapping highlights both the consolidation of established research cores and the emergence of novel thematic directions, illustrating the dynamic evolution of quantum computing toward increasingly diversified research agendas.

Horizontal lines represent the interquartile range (Q1–Q3) of publication years for each term; bubble centers indicate the median year of appearance, and bubble size is proportional to the term's total frequency. This visualization reflects both the historical onset and recent prominence of research topics.

3.5 Translational and industrial ecosystem

The industrialization of quantum computing is unfolding through the simultaneous interplay of public scientific investment and private sector mobilization. While foundational

Table 7 Major public funding agencies supporting quantum computing research (1980–2025), based on acknowledged funding sources in the analyzed dataset. The table reports the number of documents explicitly linked to each funding body

Funding sponsor	Documents
National Natural Science Foundation of China	3097
National Science Foundation	2447
European Commission	2089
Ministry of Science and Technology of the People's Republic of China	1741
U.S. Department of Energy	1271
U.S. Department of Defense	1166
Horizon 2020 Framework Programme	1060

research has been primarily supported by national and supranational funding agencies, translational applications are increasingly driven by both public research initiatives and emerging industrial actors seeking competitive advantage. This dual structure has shaped the current expansion of the quantum ecosystem from theoretical development toward early commercial relevance.

At the policy level, large-scale national and multinational funding programs have established the scientific foundations required for quantum innovation (Table 7). The National Natural Science Foundation of China (NSFC) has supported over 3000 quantum-related projects, reflecting China's strategic prioritization of next-generation information technologies. The U.S. National Science Foundation (NSF) has similarly awarded nearly 2450 grants, while the European Commission—primarily through Horizon 2020 and related programs—has funded more than 2000 projects. Additional contributions from China's Ministry of Science and Technology (MoST), the U.S. Department of Energy (DOE), and the U.S. Department of Defense (DoD) have further strengthened basic and applied research capacities, with particular emphasis on infrastructure development, quantum sensing, secure communication, and defense applications. Together, these six agencies—NSFC, NSF, European Commission, MoST, DOE, and DoD—account for the vast majority of public-sector backing in quantum-computing research, illustrating how both national priorities and supranational collaborations have jointly propelled the field from proof-of-principle experiments toward early commercial deployments.

The dominance of these public funding bodies in the bibliometric metadata has profound implications for the structure of the field previously identified in Fig. 10. The high centrality of the NSFC, NSF, and European Commission suggests that the transition from theoretical algorithms to NISQ-era applications is not yet driven by pure market dynamics, but rather by a "state-led industrialization" model. These agencies act as the primary drivers de-risking the translation of foundational theories (the red cluster in co-citation analysis) into experimental hardware (the blue cluster). Consequently, the bibliometric evidence indicates that the global quantum ecosystem remains structurally dependent on strategic public financing to sustain the publication growth observed since 2015.

4 Conclusions

This study has presented a comprehensive bibliometric mapping of the global quantum computing research ecosystem over the period 1980–2025. By integrating publication trends, citation performance, collaboration structures, conceptual evolution, and translational developments, the analysis delineates the complex dynamics that have driven the field's rapid expansion from theoretical foundations to emerging industrial applications.

The quantitative data confirm that quantum computing has transitioned from its early algorithmic and information-theoretic roots into a highly multidisciplinary domain encompassing hardware engineering, software development, cryptography, materials science, chemistry, and finance. The exponential growth in publication output, particularly since 2015, reflects both scientific maturation and large-scale public and private investment.

The structural analysis of collaboration networks reveals a tightly interconnected global research system, with strong international partnerships coexisting alongside concentrated national efforts—particularly in the United States, China, and Europe. Co-citation and keyword analyses confirm and quantify this expected "dual-core" intellectual architecture. Our metrics demonstrate that while the field is divided between foundational theory and NISQ-era applications, these domains remain structurally coupled by specific algorithmic bridges (e.g., VQE, QAOA) rather than fragmenting into isolated silos.

Translational activities are accelerating, with quantum computing now being actively explored across multiple industrial sectors, including healthcare, finance, energy, climate science, materials engineering, and chemistry. These efforts are supported by unprecedented levels of public-sector funding from major national and supranational agencies, as well as by significant private-sector investment from leading technology companies and financial markets. The emergence of financial instruments such as quantum-focused ETFs underscores growing investor confidence in the field's medium- and long-term prospects.

Nonetheless, many technical challenges remain before large-scale fault-tolerant quantum computing can be fully realized. Current efforts continue to focus on improving hardware coherence, error correction, qubit scaling, and algorithmic robustness. In parallel, the hybridization of quantum and classical approaches offers near-term opportunities for practical advantage in selected domains.

Overall, the bibliometric evidence presented here illustrates not only the remarkable scientific progress of quantum computing but also its progressive integration into broader technological and economic ecosystems. Continued interdisciplinary collaboration, sustained funding, and coordinated policy efforts will be essential to drive the field toward its next phase of scalable, fault-tolerant, and industrially transformative quantum computing systems.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1140/epjqt/s40507-026-00464-4.

Additional file 1. (PDF 224 kB)

Author contributions

D.C.-T. and A.S.-G. conceived the study, curated the dataset, performed the analyses, and wrote the main manuscript text. Á.P. and R.G.-F. supervised the research, provided critical feedback on the analytical framework and interpretation of results and secured project funding. All authors reviewed and approved the final version of the manuscript.

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Data availability

All data processing workflows, custom scripts, and analysis pipelines are openly accessible at: https://github.com/DanielCondeTorres/BIBLIOMETRIC.

Declarations

Competing interests
The authors declare no competing interests.

Declaration of AI and AI-assisted technologies in the writing process
During the preparation of this work the authors used GPT-5 from OpenAI in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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