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SURVEY

Mapping the Landscape of Quantum Computing and High Performance Computing Research Over the Last Decade

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ABSTRACT Quantum Computing (QC) is a rapidly evolving research field that has garnered significant attention due to its potential to revolutionize various domains such as cryptography, optimization, and machine learning. In this article, we conduct an extensive analysis of the evolution of QC research within the realm of High Performance Computing (HPC) over a span of ten years, up to 2023. Through bibliometric analysis and advanced science mapping techniques, we uncover key thematic areas that have emerged in the field, including quantum algorithms, simulation, parallel-computing, deep learning, machine learning, and encryption. This analysis highlights the interdisciplinary nature of QC, which intersects with disciplines such as physics, mathematics, computer science, and materials science. Furthermore, our study elucidates the close relationship between HPC and QC, showcasing how advancements in one field can significantly impact the other. The findings of this study not only provide valuable insights into the past trends and research landscape but also serve as a guide for future research directions, enabling the advancement of knowledge and fostering innovation in computer science. Additionally, our analysis sheds light on the global distribution of research contributions, identifying countries and regions that have made significant strides in QC research, thus presenting potential collaboration opportunities. Overall, this comprehensive study contributes to a deeper understanding of the development of QC within the realm of HPC, offering valuable insights and paving the way for future advancements in this exciting field.

INDEX TERMS Quantum computing, high performance computing, bibliometrics, science mapping, co-occurrence analysis, machine learning.

I. INTRODUCTION

High Performance Computing (HPC) can be defined as the set of methods and techniques developed to solve advanced computation tasks [1]. HPC is typically linked to i) supercomputers with very specific architectures based on parallel computing or cluster computing [2], and ii) distributed and virtualized architectures based on grid computing or cloud computing [3]. The study and development of HPC have been essential to achieving major technological breakthroughs during recent decades. This is evidenced by the wide range of research fields in which HPC has been applied: big data [4], bioinformatics [5], signal processing [6], privacy [7], efficient resources management [8], weather modeling [9], manufacturing processes [10], and business management [11], among others. Naturally, most of these tasks would not have been feasible using conventional computational techniques. Over the years, HPC has faced challenges such as power consumption, data management, and hardware limitations [12], [13], [14]. With

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the exponential growth in computational demand, managing power consumption has become crucial to prevent overheating and optimize energy efficiency. Furthermore, efficiently handling vast amounts of data, often generated by complex simulations or big data analytics, presents a significant challenge for HPC systems. Additionally, hardware limitations, including memory bandwidth and processor speed, constrain the performance scalability of HPC architectures.

In this context, Quantum Computing (QC) has emerged as a new technology that drastically modifies the computer architecture using the fundamentals of quantum mechanics [15]. With this new approach, certain problems with a large computational cost can be solved substantially faster than with classical computers [16], [17], [18], [19], [20], [21], [22], [23]. In recent years, QC has faced significant challenges related to achieving and maintaining qubit coherence, mitigating errors resulting from environmental interference and noise, and increasing scalability. Although it is still at an early stage of development, QC is closely linked to the HPC philosophy and is being used to solve certain tasks in different research fields such as resource management in design activities using the ''digital twin'' approach [24], finance management [25], the allocation of optimal combinations of raw materials to achieve an optimal end product [16], traffic navigation optimization [26], and the development of biomedical techniques based on the analysis of patients' genomes [17], among many others. This confirms the possibility of developing quantum algorithms to outperform classical computation.

However, although there are literature reviews on HPC [27] and QC [28], to the best of our knowledge there is a gap concerning the current state of research in the field of HPC and QC with the need to consider both issues simultaneously in a review study. Indeed, the intersection of HPC and QC presents a set of challenges and opportunities. As computational demands continue to grow, the integration of QC into HPC infrastructure offers a promising avenue to overcome existing limitations. This convergence has the potential to revolutionize computational methods, enabling the tackling of complex problems that are currently infeasible with traditional computing architectures. Despite the rapid advancements in the QC field, there is a noticeable lack of comprehensive studies that examine the synergies and potential integration strategies of both fields. This absence is particularly evident in the exploration of how QC can complement and enhance the capabilities of HPC to create more efficient, powerful, and versatile computing systems. This paper addresses a literature gap by conducting a comprehensive bibliometric analysis, exploring individual trajectories and collaborative trends between QC and HPC. By identifying key themes and collaborative dynamics, the study contributes to a holistic understanding of the evolving landscape, emphasizing the significance of studying these technologies collectively for future advancements.

Thus, the purpose of this paper is to analyze the evolution of QC and HPC research over the ten years up to 2023. Particularly, our work aims to identify the themes that have captured the greatest attention from the research community in this area of knowledge. To gain a better understanding of the research landscape in QC and HPC, we conducted a comprehensive bibliometric performance analysis that analyzed several key performance indicators such as published articles, citations received, most cited papers, most productive journals and authors, and the geographical distribution of publications. In addition, we performed a science mapping analysis based on co-word networks and bibliographic coupling to identify the most relevant research themes addressed and to evaluate the scientific contributions in this field. To the authors' knowledge, this is the first literature review that studies recent QC and HPC research.

This paper is organized as follows. Section II presents the methodology and data set used in this study. Then, Section III describes the bibliometric performance and science mapping analyses carried out. Section IV delves into the discussion. Finally, conclusions are drawn in Section V.

II. METHOD

This section presents the method used in this study. First, the different steps of the methodology and a detailed explanation of the software used in the study are reported. Then, the data collection and pre-processing procedure is described.

A. METHODOLOGY

As mentioned above, the purpose of this study is to provide a thematic landscape of the research on QC and HPC using SciMAT [29] and VOSviewer [30] software. SciMAT identifies topics in a longitudinal science mapping analysis based on co-word bibliographic networks, while VOSviewer generates maps and different types of bibliographic analyses such as citation, co-citation, co-authorship, co-occurrence, and bibliographic coupling. Specifically, the study uses SciMAT to perform a bibliometric performance analysis and a science mapping analysis based on co-word networks during the period 2014-2023. Then, VOSviewer is used to complement the science mapping analysis through a keywords co-occurrence analysis and a bibliographic coupling analysis to cluster the literature into the main research areas.

The SciMAT software is used to conduct a longitudinal science mapping analysis, following the methodology proposed by Cobo et al. [31]. Initially, research themes are detected through keyword co-occurrence, where each document's keywords are used to build a network. In this network, nodes represent keywords and edges connect nodes that co-appear in a set of documents. The strength of the co-occurrence relationship is measured by the weight of the edge connecting the nodes.

The second step addresses the visualization of research themes and thematic networks. Centrality (external interaction between networks that represents the theme's relevance) and density (network's internal cohesion that can be understood as the topic's development) dimensions are used to characterize each topic, while a graphic representation

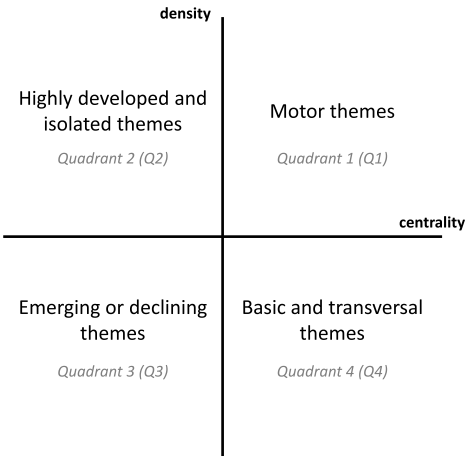


FIGURE 1. Strategic diagram adapted from Cobo et al. [29].

is created using a strategic diagram and thematic networks (see Figure 1). The use of these two dimensions enables to represent a research field as a strategic dual-axis diagram with four different categories:

- *Motor themes* (Q1): well-developed and essential themes for structuring a research field.
- *Basic and transversal themes* (Q4): relevant but still not fully developed themes in the field.
- *Highly developed and isolated themes* (Q2): well-developed topics with marginal importance in the field.
- *Emerging or declining themes* (Q3): poorly or marginally developed themes.

In this spatial representation, each research theme is depicted as a sphere, with its volume directly proportional to the number of documents associated with it.

The third phase entails discovering the thematic areas. In this study, we use VOSviewer to identify the major research areas in the field. For this, a bibliographic coupling analysis is carried out based on the publications considered in this study. Bibliographic coupling entails the presence of two documents that have at least one reference in common [32] and measures the existing association between two citing publications.

B. DATASET

To conduct bibliometric performance and science mapping analyses on QC and HPC literature, a systematic collection of relevant publications was performed. The study utilized scientific documents extracted from the Web of Science (WoS) Core Collection database, with a search conducted in February 2024 using the keywords ''quantum computing'' and ''high performance computing'' in the ''Abstract'' and ''Author Keywords'' fields. An advanced query was used, with the search string AB = (''quantum computing'' AND ''high performance computing'') OR AK = (''quantum computing'' OR ''high performance computing''), which retrieved 11.175 initial results. However, the corpus was further refined and delimited using exclusion criteria, including publication year (2014-2023 period), document type (journal articles[1]), research area (Computer Science), and language (English). After this process, a total of 3.435 papers were identified in the WoS Core Collection for analysis.

The 3.435 records, containing their full descriptions such as title, authors, source, abstract, keywords, affiliations, and citations, were exported to a plain text file and used to construct the knowledge base for the science mapping analysis in SciMAT. To ensure data quality and identify potential research themes, a de-duplication process was conducted where words and concepts with the same meaning were grouped together (e.g., ''QC'', ''QUANTUM COMPUTING'', ''QUANTUM-COMPUTATION'', and ''QUANTUM-COMPUTING-(QC)'' were merged as ''QUANTUM COMPUTING''). Additionally, meaningless terms in the context of this study, such as ''MODEL'', ''SIMULATION'', ''PERFORMANCE'', and ''SYSTEMS'', were omitted. Preprocessing is a crucial stage in obtaining reliable results in science mapping analysis [29]. The total number of unique keywords used in the papers was 12,013.

To conduct the science mapping analysis of QC and HPC research, two consecutive time periods were established using the SciMAT period manager. Instead of covering similar lengths of time, the ten-year period from 2014-2023 was divided into subperiods of 2014-2020 and 2021-2023 based on comparable production levels, as this was considered the most suitable option [33]. The first period included 1,784 papers, while the second included 1,651 papers, resulting in a longer first period, which was necessary for adequate analysis and theme detection. This allowed for comparison of the publication volumes in the two subperiods.

III. RESULTS

A. BIBLIOMETRIC PERFORMANCE ANALYSIS

This section reports the evolution of research on QC and HPC through the analysis of the following bibliometric indicators: published papers, citations received, most cited papers, most prolific journals, most productive authors, contributing institutions, and geographic distribution of publications.

The bibliometric performance analysis is structured into two different parts: (a) production and impact of publications, and (b) production of the most relevant scientific actors (journals, authors, affiliations, and countries).

To gain a more comprehensive understanding of the research literature, a separate analysis was conducted for papers related to QC and HPC. Specifically, 1,319 papers were identified that addressed QC, 1,965 documents that focused on HPC, and only 151 articles that examined both QC and HPC together.

1) PUBLICATION AND CITATION TREND ON QC AND HPC

Figure 2 reports the publication and citation trends in the field under study. As can be observed, there has been a growing

[1]We refined our search to articles but retained proceeding papers, given their dual categorization as both articles and proceeding papers in the WoS database. This decision ensures a comprehensive view of the research landscape by incorporating the insights offered by proceeding papers.

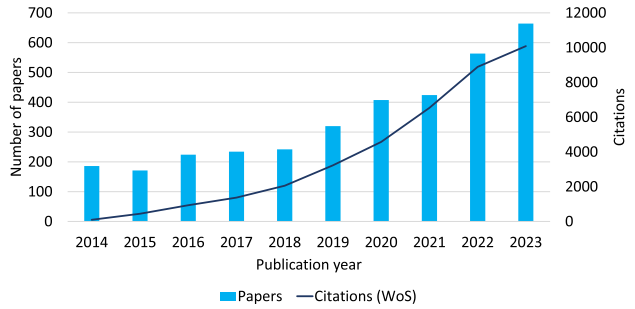


FIGURE 2. Distribution of publications and citations on QC and HPC by year (2014-2023).

interest in the QC and HPC topic since 2014. Regarding the number of publications, 2023 was the most productive year with more than 600 papers. The already increasing number of articles dealing with this topic is expected to continue growing, as suggested by the evolution presented in Figure 2. Concerning the number of citations, the last three years –2021, 2022, and 2023– saw an exponential increase, indicating that QC and HPC issues are gaining influence in the research literature.

2) MOST CITED PAPERS ON QC AND HPC

Table 1 shows the most cited publications on QC and HPC during the 2014-2023 period based on the total number of citations in the WoS database. Highly cited papers are widely regarded as a crucial indicator of the significance and influence of a particular research area. Therefore, identifying highly cited papers is crucial in determining the development of a field, as they often indicate the interest of the scientific community in a particular topic [44], [45]. Based on total citations, Darriba et al. [34] is the most cited paper in the field, considering both total citations and relative citations (total citations divided by the number of years since publication). The documents gathered in this table deal with HPC for phylogenetic selection [34], qubits [35], HPC in optics [46], machine learning and artificial intelligence [36], [39], supercomputers [40], QC in photonics [38], big data [37], [41], quantum annealing [47], and optimization [42], [43].

3) MOST PROLIFIC JOURNALS ON QC AND HPC

Table 2 presents the most prolific journals on QC and HPC during the 2014-2023 period. In total, there were 807 distinct sources, encompassing both journals and conference proceedings. As can be observed, *IEEE Access* is the most representative source in this field with 196 papers on QC and HPC since 2014. *IEEE Access* is multidisciplinary, online-only, gold fully open access journal that emphasizes application-oriented and interdisciplinary papers in all IEEE fields of interest. The Top5 of most prolific journals on this topic is characterized by their high impact and influence, as they are categorized in Q1 (*IEEE Transactions on Parallel and Distributed Systems* and *Computer Physics Communications*) and Q2 (*IEEE Access*, *Concurrency and Computation: Practice & Experience,* and *Journal of Supercomputing*) JIF quartiles in the Computer Science category of the 2022 Journal Citation Reports. The reputation of these journals reflects the quality and importance of the extant research dealing with QC and HPC.

After analyzing the literature on QC and HPC separately, it was found that *IEEE Access* is the most distinguished journal in publications exclusively related to QC. *Quantum Information Processing* and *IEEE Transactions on Information Theory* follow it in that order. In the case of HPC literature, *Concurrency and Computation: Practice & Experience* stands out as the most prolific journal followed by the *Journal of Supercomputing* and *IEEE Transactions on Parallel and Distributed Systems*.

4) MOST PRODUCTIVE AUTHORS ON QC AND HPC

Table 3 shows the most productive authors investigating QC and HPC. Professors Siddhartha Bhattacharyya, Majid Haghparast, and Lajos Hanzo are the most contributing authors to this field with 19 papers. However, this table indicates that, as yet, no authors dominate the field. Lastly, note that authors with the same number of publications on this topic have been reported in the same position in the ranking.

When examining the literature on QC, Professors Bhattacharyya, Haghparast, and Hanzo emerged as the most productive researchers. Meanwhile, in the field of HPC, Professors Plaza, Quintana-Orti, and Tourino were found to be the most prolific contributors.

5) MOST CONTRIBUTING AFFILIATED INSTITUTIONS TO QC AND HPC

Table 4 reports the most contributing institutions to QC and HPC during the 2014-2023 period. As can be seen, the US Department of Energy (DOE) is the undisputed leader in this Top5 with 246 documents on QC and HPC. One interesting feature of this list is that most of the affiliated institutions are research centers and associations instead of single universities. This would indicate that QC and HPC research is mostly undertaken by specialized institutions rather than university research groups. The reason for this might be found in the large number of resources and amount of funding needed to carry out investigations in this area of knowledge. Moreover, two out of five institutions are located in the USA, and the two remaining are located in France. Lastly, note that a single document may have more than one affiliated institution.

The institutions that have made the most contributions to HPC literature are ranked as follows: United States Department of Energy (USA), Oak Ridge National Laboratory (USA), Centre National de la Recherche Scientifique (France), Argonne National Laboratory (USA), and Chinese Academy of Sciences (People's Republic of China). Similarly, the United States Department of Energy (USA) is the most prolific institution when it comes to research focused on QC, followed by Chinese Academy of Sciences (People's Republic of China), University of London (England), and University of California System (USA).

TABLE 1. Most cited papers on QC and HPC (2014-2023).

Rank	Total Citations	Title, Reference	Citations per year
1	812	ModelTest-NG: A New and Scalable Tool for the Selection of DNA and Protein Evolutionary Models [34][2]	203
2	613	Superconducting Qubits: Current State of Play [35][1]	153.3
3	449	Machine learning & artificial intelligence in the quantum domain: a review of recent progress [36][1]	74.8
4	401	Big data in healthcare: management, analysis and future prospects [37][1]	80.2
5	369	Photonic quantum information processing: a review [38][1]	73.8
6	338	Parameterized quantum circuits as machine learning models [39][1]	67.6
7	296	The Sunway TaihuLight supercomputer: system and applications [40][2]	37
8	282	Big Data for Remote Sensing: Challenges and Opportunities [41][2]	35.3
9	273	From the Quantum Approximate Optimization Algorithm to a Quantum Alternating Operator Ansatz [42][1]	54.6
10	265	Quantum autoencoders for efficient compression of quantum data [43][1]	37.9

Note: [1]*QC,* [2]*HPC*

TABLE 2. Most prolific journals on QC and HPC (2014-2023).

Rank	Journal	Papers	JIF
1	IEEE Access	196	3.9
2	Journal of Supercomputing	106	3.3
3	Concurrency and Computation: Practice & Experience	104	2.0
4	IEEE Transactions on Parallel and Distributed Systems	82	5.3
5	Computer Physics Communications	80	6.2

Note: JIF – Journal Impact Factor 2022 (Clarivate Journal Citation Reports)

TABLE 3. Most productive authors on QC and HPC (2014-2023).

Rank	Author	Papers
1	Bhattacharyya, Siddhartha; Haghparast, Majid; Hanzo, Lajos; Ng, Soon Xin	19
2	Gonzalez-Dominguez, Jorge	16
3	Quintana-Orti, Enrique S.	15
4	Botsinis, Panagiotis; Plaza, Antonio	14
5	Yang, Guangwen	13

TABLE 4. Most contributing institutions to QC and HPC (2014-2023).

Rank	Affiliated institution	Papers
1	United States Department of Energy (USA)	294
2	Centre National de la Recherche Scientifique (France)	103
3	Chinese Academy of Sciences (People's Republic of China)	95
4	University of California System (USA)	82
5	Domain of the Swiss Federal Institutes of Technology (Switzerland)	69

6) GEOGRAPHIC DISTRIBUTION OF PUBLICATIONS ON QC AND HPC

Table 5 and Figure 3 show the geographic distribution of publications on QC and HPC since 2014. The USA is the most productive country in the QC and HPC field with a total of 1,004 publications, far ahead of the following country in the number of papers, i.e., the People's Republic of China with 540 documents. Figure 3 supports this information on the geographic location of documents on QC and HPC. The geographic distribution of the works reveals that this topic is being intensely investigated in America, Asia, and Europe.

TABLE 5. : Geographic distribution of publications on QC and HPC (2014-2023).

Rank	Country	Papers
1	USA	1,004
2	People's Republic of China	540
3	Germany	322
4	Spain	276
5	England	269

After conducting an analysis of the literature on QC, it was observed that the USA, People's Republic of China, India, England, and Germany were the most productive countries in terms of the number of papers published, listed in descending order. In the case of HPC research, the countries with the highest productivity were the USA, Spain, People's Republic of China, Spain, Germany, France, and England, also listed in descending order.

B. SCIENCE MAPPING ANALYSIS

The science mapping analysis is structured into two main interconnected parts: 1) a longitudinal analysis of the papers to identify the most relevant topics in the QC and HPC field during each of the periods and an evaluation of their development, and 2) a bibliographic coupling analysis to discover the main research areas based on the interrelationships between documents in the entire period of analysis.

1) LONGITUDINAL ANALYSIS OF PUBLICATIONS

The longitudinal science mapping analysis, conducted using the SciMAT software and following the methodology proposed by Cobo et al. [31], comprises several key steps. Initially, research themes are identified through keyword co-occurrence analysis, constructing a network where nodes represent keywords and edges connect co-occurring nodes, with the strength of the relationship determined by edge weight. The second step involves visualizing research themes and thematic networks, employing centrality and density dimensions to characterize each topic. A strategic dual-axis diagram categorizes themes into motor, basic and transversal, highly developed and isolated, and emerging or declining themes. Finally, each research theme is represented as a

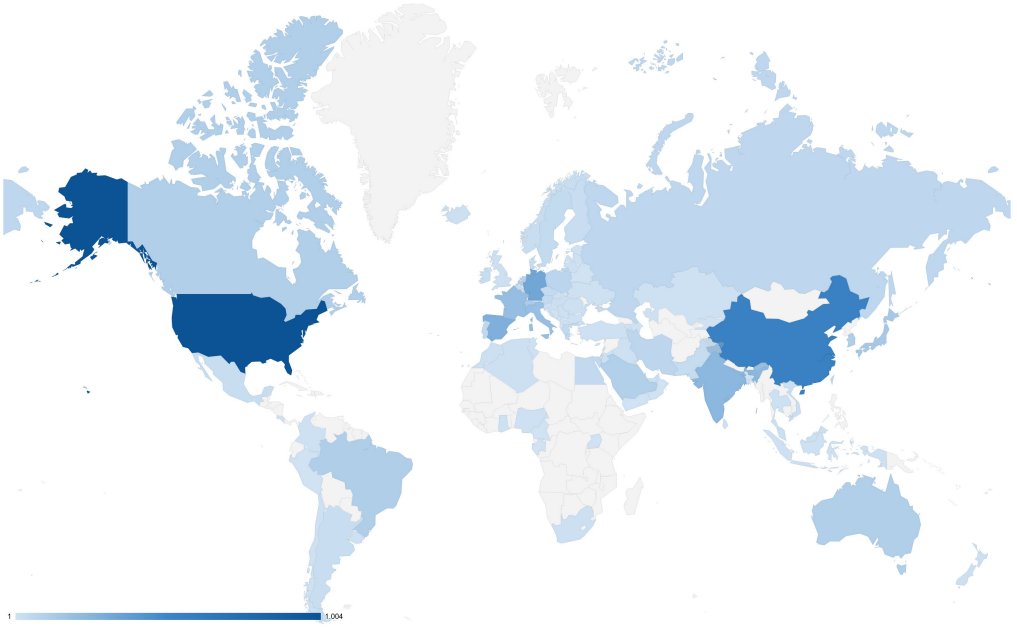


FIGURE 3. Geographic locations of the most productive countries in QC and HPC (2014-2023).

sphere in a spatial depiction, with its volume directly proportional to the number of associated documents. A comprehensive explanation of this procedure can be found in Section II-A.

Figure 4 displays two strategic diagrams that analyze the most significant research themes in the field of QC and HPC between 2014 and 2023. In these diagrams, research themes are visualized as spheres, and their sizes correspond to the number of papers associated with each theme.

TABLE 6. Performance of themes during 2014-2020 on QC and HPC.

Period 1 (2014-2020)			
Research theme (quadrant)	Papers	% of total	Citations
Quantum-Computing (Q1)	490	27.5	11,255
Machine-learning (Q1)	163	9.1	5,432
FPGA (Q4)	93	5.2	1,470
Reversible-logic (Q2)	49	2.7	1,038
Resource-management (Q2)	41	2.3	415
Image-processing (Q1)	40	2.2	600
OpenMP (Q3)	40	2.2	774
Cryptography (Q3)	34	1.9	960
Grover's-quantum-search-algorithm (Q1)	12	0.7	242

a: PERIOD 1 (2014-2020)

According to the strategic diagram in Figure 4a, the field under study comprised ten research themes during 2014-2020, with six themes considered fundamental given their contribution to the development of the field (motor and basic and transversal themes): *high-performance-computing*, *quantum-computing*, *machine-learning* [36], [39], *FPGA* [48], [49], *image-processing* [50], and *Grover's-quantum-search-algorithm* [51], [52].

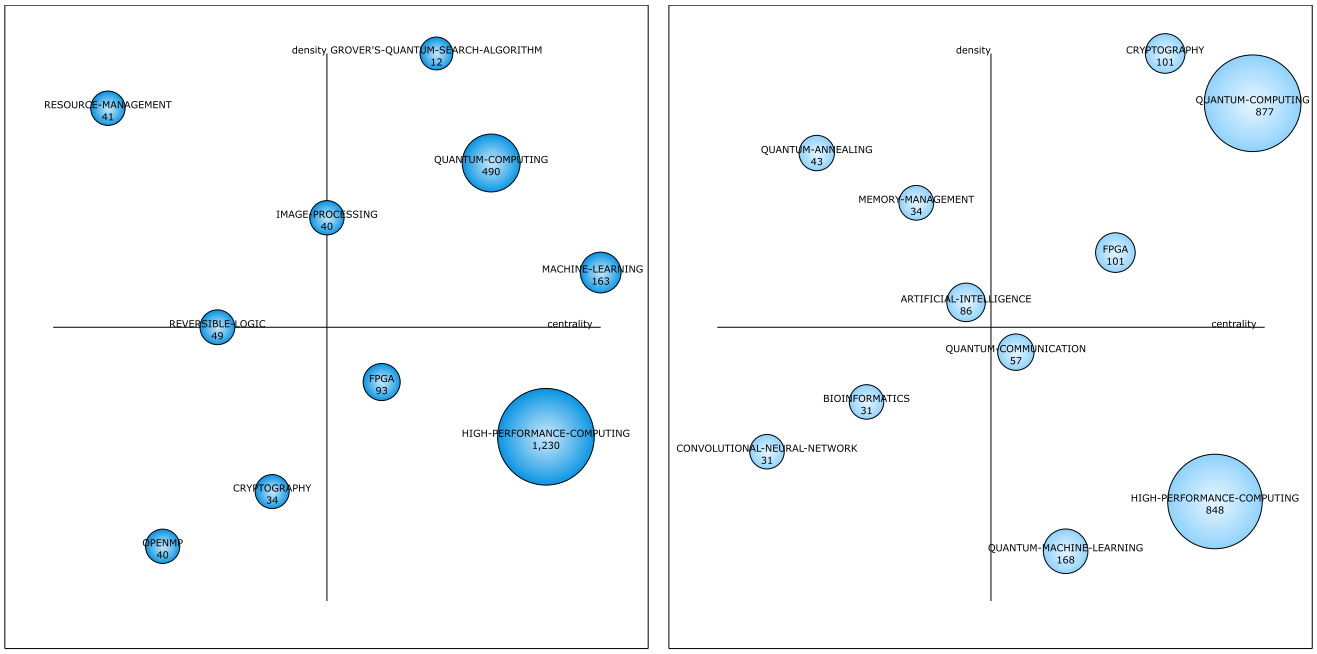
Table 6 displays the performance indicators, including the number of publications, relative share of the total, and citations received by publications, for the themes identified during the period. Based on these indicators, *high-performance-computing* and *quantum-computing* are the main research themes during these years. *Quantum-computing* is a motor theme, while *high-performance-computing* is a basic and transversal theme, both in continuous development during 2014-2020. The *High-performance-computing* theme includes works related to parallel computing [53], [54], cloud computing [55], [56], energy efficiency [57], and GPU [58], [59], among others. The *Quantum-computing* theme deals with papers about qubits [35], [60], quantum algorithms [42], [61], quantum circuits [39], [62], quantum information and communication [63], [64], computational complexity [52], [65], etc.

In terms of the number of publications and citations, *high-performance-computing* has attracted much more attention from the research community during this period than *quantum-computing*, and papers dealing with HPC issues have had a major influence in the field. Almost 70% of the 1,784 papers in this period have addressed issues related to HPC. This may be due to the later appearance of QC-related issues compared to the wide tradition of HPC literature.

b: PERIOD 2 (2021-2023)

According to the strategic diagram in Figure 4b, eleven research themes can be identified in the QC and HPC literature since 2021. Of these, six are considered to be major themes (motor and basic and transversal themes) in the period 2021-2023: *quantum-computing*, *high-performance-computing*, *quantum-machine-learning*, *cryptography*, *FPGA*, and *quantum-communication*.

Performance measures in Table 7 show that this field is increasing in importance compared to the previous period (2014-2020). In this second period, the research themes *quantum-computing* and *high-performance-computing* per-



(a) Period 2014-2020.

(b) Period 2021-2023.

FIGURE 4. Strategic diagrams.

TABLE 7. Performance of QC and HPC themes during 2021-2023.

Period 2 (2020-2023)			
Research theme (quadrant)	Papers	% of total	Citations
Quantum-Computing (Q1)	877	53.1	4,961
High-Performance-Computing (Q4)	848	51.4	3,570
Quantum-machine-learning (Q4)	168	10.2	853
Cryptography (Q1)	101	6.1	684
FPGA (Q1)	101	6.1	459
Artificial-Intelligence (Q2)	86	5.2	651
Quantum-communication (Q4)	57	3.5	513
Quantum-annealing (Q2)	43	2.6	133
Memory-management (Q2)	34	2.1	231
Bioinformatics (Q3)	31	1.9	79
Convolutional-neural-network (Q3)	31	1.9	113

sist as fundamental and pivotal motor themes driving advancements in the field. Focusing on some specific topics, *cryptography* addresses works related to security [66], protocols [67], privacy [68], and authentication [69]. The *FPGA* research theme includes works on computer architecture [70], encryption [71], and parallel processing [72]. Lastly, *artificial-intelligence* addresses works related to neural networks [62], [73], performance evaluation [74], [75], and robotics [76]. It can be seen that research themes dealing with quantum issues such as *quantum-machine-learning* [77], *quantum-communication* [78], and *quantum-annealing* [79] have increased during the last few years.

2) KEYWORD CO-OCCURRENCE ANALYSIS

Keyword co-occurrence is observed when two or more keywords appear together in one or more publications [80]. Figure 5 presents the co-occurrence of authors' keywords over time in the field of QC and HPC. VOSviewer was used to generate a visual representation of the keyword network. The nodes represent keywords, and their size is proportional to the number of occurrences, while the links indicate the co-occurrences, i.e., the number of publications in which each pair of keywords occur together.

Complementing the previous longitudinal analysis, Figure 5 reports two major topics, HPC and QC, but a variety of particular issues are addressed by the research in this field. HPC is related to different topics such as parallel computing [53], cloud computing [55], big data [81], load balancing [82], and simulation [83]. QC encompasses issues related to quantum algorithms [42], quantum circuits [39], quantum entanglement [63], quantum annealing [79], logic gates [84], reversible logic [85], qubits [60], and genetic algorithms [86]. Midway between HPC and QC, covering aspects such as computational modeling [87], GPUs [58], performance analysis [74], energy efficiency [57], mathematical models [88], and computer architecture [70]. Similarly, the machine learning topic deals with deep learning [89], artificial intelligence [36], neural networks [62], quantum machine learning [77], and computational complexity [52]. Cryptography is identified as another area related to QC that deals with quantum communication [78], complexity theory [90], security [66], privacy [68], FPGAs [49], protocols [67], Internet of Things [91], lattices [92], and quantum cryptography [93].

3) BIBLIOGRAPHIC COUPLING ANALYSIS

Bibliographic coupling analysis measures the association between two citing publications and has frequently been used to identify current trends in the literature [33], [94]. Therefore, it provides valuable information for content analysis of the documents included in the study. In this work,

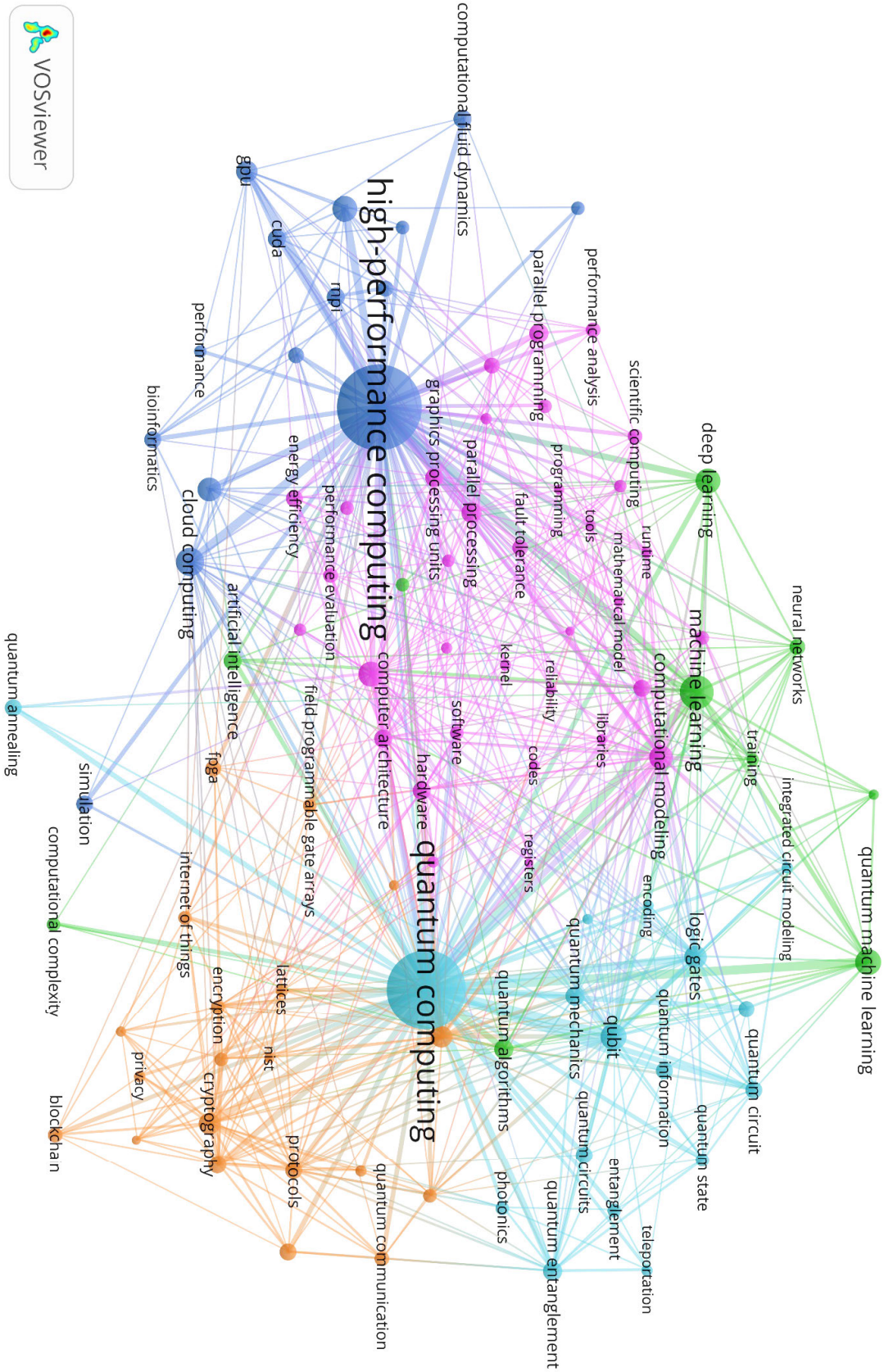


FIGURE 5. Co-occurrence of QC and HPC keywords.

TABLE 8. Main clusters in the QC and HPC field and their research focuses.

Cluster	Number of papers	Research focus
1	567	HPC applications
2	149	QC fundamentals
3	117	Quantum machine learning
4	103	Quantum communications
5	64	QC applications

bibliographic coupling has been used to identify the current trends in the QC and HPC field through the discovery of the main research areas.

Figure 6 shows the QC and HPC bibliographic network. Each label or node represents a scientific paper, and the size of the label indicates the item's weight in the network in terms of citations. The links represent the bibliographic couplings and their thickness illustrates the number of references that any two nodes share. The color of the labels is determined by the cluster or research area to which the item belongs. Lastly, the distance between any two nodes in the network represents an approximation of the items' relatedness [30].

As can be observed, five clusters can be distinguished in Figure 6. Clusters 2, 3 and 4 are very close, which indicates that the connection between these documents is strong. Similarly, Clusters 1 and 5 are reasonably close to each other, although the latter is spread out across the map. The strongest links are shown to be between Clusters 2 and 3, which indicates that these research areas are highly interconnected in terms of shared references.

To facilitate content analysis of the bibliographic network, the most influential works in each cluster have been deeply analyzed to discover the thematic characteristics of each group of papers. Table 8 summarizes the four thematic clusters in the QC and HPC field and their research focuses are identified through a deductive process from the content analysis carried out. In conclusion, as a result of this clustering process, the reader can distinguish two different areas of research (i.e., HPC and QC) that are, in turn, closely linked.

More specifically, papers included in Cluster 1 mainly address HPC applications related to big data [37], [41], [55], [95], [96], [97], energy consumption and management [57], [98], healthcare sector [37], smart cities [95], [97], and transportation [99].

Cluster 2 includes the literature most oriented toward studying and analyzing the QC fundamentals. There are papers focusing on superconducting quantum computing [35], [60], [100], quantum entanglement [63], [101], quantum control [102], [103], and quantum information [38], [104].

Cluster 3 deals with quantum machine learning and focus on different themes such as quantum neural networks [62], [73], [77], quantum information processing [36], [43], [89], tensor network [105], and simulation methods for quantum computers [42], [106].

The literature included in Cluster 4 is more focused on quantum communications, including papers on blockchain cryptography [93], security [78], [91], [107], wireless communication [64], [108], and computational complexity systems [52], [65], [109], [110].

Lastly, as can be inferred from Figure 6, Cluster 5 includes papers that are directly related to QC applications. Most of the works have focused on meta-heuristic methods [111], [112], [113], optimization algorithms [114], [115], [116], bio-inspired algorithms [117], [118], [119], and IoT applications [120], [121], [122].

IV. DISCUSSION

The longitudinal analysis spanning two distinct periods unveils significant shifts in the research landscape of QC and HPC. In Period 1 (2014-2020), high performance computing emerged as a dominant theme alongside quantum computing, classified as fundamental motor and basic and transversal themes. While high performance computing, covering parallel and cloud computing, attracted more attention and citations, quantum computing showed steady progress, focusing on qubits and quantum algorithms. Notably, quantum computing emerged as a motor theme, indicating its pivotal role. In Period 2 (2021-2023), the research landscape expanded, with themes like quantum machine learning, cryptography, and quantum communication gaining prominence alongside quantum and high performance computing. Performance measures indicate increased field importance, with QC and HPC remaining fundamental motor themes. The emergence of new themes reflects evolving research interests, particularly in quantum machine learning and quantum communication. These findings underscore the field's dynamism and ongoing pursuit of innovative solutions in QC and HPC.

The keyword analysis uncovers a wide range of topics in both HPC and QC domains. HPC research spans parallel computing, cloud computing, big data, load balancing, and simulation, while QC investigations include quantum algorithms, circuits, entanglement, annealing, qubits, and genetic algorithms. Optimization-related issues, such as computational modeling, GPUs, performance analysis, energy efficiency, mathematical models, and computer architecture, intersect between HPC and QC. Additionally, machine learning covers deep learning, artificial intelligence, neural networks, quantum machine learning, and computational complexity. Cryptography, closely linked to QC, addresses quantum communication, complexity theory, security, privacy, FPGAs, protocols, IoT, and quantum cryptography. This comprehensive analysis underscores the interdisciplinary nature of research in HPC and QC, showcasing the convergence of diverse domains to advance computing technologies.

The bibliographic coupling analysis unveils five distinct clusters within the research landscape of QC and HPC. Notably, strong interconnections exist between Clusters 2, 3, and 4, highlighting a close relationship between their research areas. Specifically, Cluster 1 primarily focuses on HPC

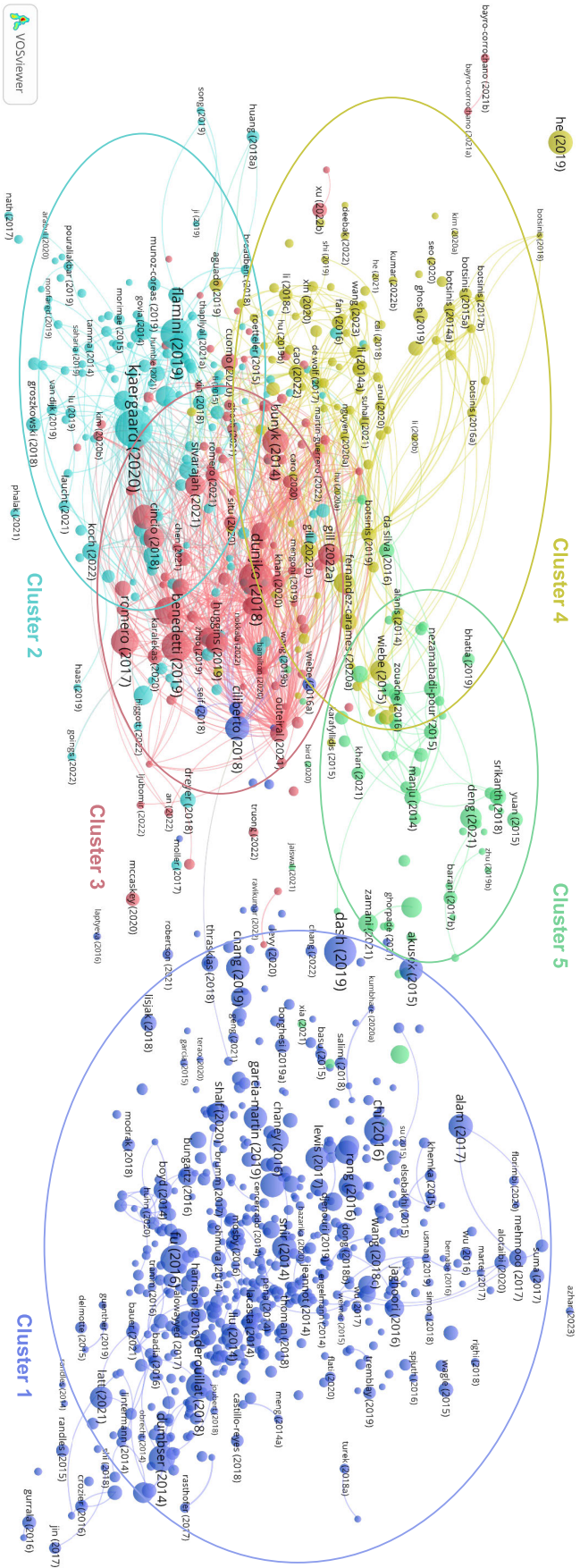


FIGURE 6. QC and HPC bibliographic network.

applications, while Cluster 2 delves into the fundamentals of QC. Clusters 3 and 4 explore quantum machine learning and quantum communications, respectively. Lastly, Cluster 5 centers on QC applications, including meta-heuristic methods and optimization algorithms. This clustering analysis provides valuable insights into the diverse thematic dimensions of research in HPC and QC, facilitating a deeper understanding of the field's multidimensional nature.

This study plays a crucial role in advancing our understanding of QC, HPC, and their intersection, addressing key challenges in both fields. QC and HPC represent distinct yet interconnected domains, each facing unique hurdles. HPC focuses on maximizing computational power and efficiency, tackling issues like parallel processing and energy consumption. Furthermore, while privacy and security concerns are not as common as efficiency and energy-saving considerations in HPC, they are becoming increasingly relevant. Conversely, QC explores the potential of quantum phenomena to revolutionize computing, grappling with challenges such as qubit coherence and error correction. By examining the evolving landscape of research in QC and HPC, this study sheds light on their interplay and highlights emerging themes like quantum-machine-learning and quantum-communication. Understanding these dynamics is essential for harnessing the full potential of QC and HPC technologies, paving the way for transformative advancements in computational science and technology.

V. CONCLUSION

The present study has examined the structure and content of the research into QC and HPC over the last decade. SciMAT and VOSviewer were used to process, analyze and visualize the 3,435 papers on QC and HPC published since 2014. In terms of bibliometric performance, the publication and citation trends and the most contributing actors have been reported (journals, authors, institutions, and countries). With respect to the science map, a longitudinal analysis is provided of the field from 2014 to 2023 (divided into two consecutive periods), as well as keywords and bibliographic coupling analyses that enable to cluster the main research themes in the field. The primary contribution of this study is the identification and examination of the research themes that have been developed by the scientific community in the field of QC and HPC, as well as their evolution over the past decade. This study provides useful insights into the development of the QC and HPC areas of knowledge and can encourage further research and practical applications to be studied and implemented.

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