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Quantum Science and Technology (QST) Education-A Bibliometric and Content Analysis

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ABSTRACT

Quantum Science and Technology (QST) has rapidly advanced over the last two decades, revolutionizing various aspects of our lives. As the future becomes increasingly quantum-focused, industries demand skilled professionals with competent knowledge and expertise. Numerous studies have explored quantum education to meet the growing demand for a skilled workforce in quantum-related industries. However, a comprehensive bibliometric analysis encompassing the entire spectrum of QST education at all educational levels is still lacking. Thus, this study applied both bibliometric and content analysis on bibliographic data retrieved from the Scopus database to address two objectives: a) to provide collective insights into QST education studies quantitatively, and b) to outline the evolving conceptual structure of this field. Through performance analysis, citation analysis, and co-citation and co-word analysis, this paper provides a comprehensive outlook on the landscape and evolving intellectual structure of QST education research. Furthermore, scientific mapping techniques were utilized to uncover the intellectual structure, thematic evolution, and collaborative networks within the field. The content analysis identified focal points for each QST education research cluster. In sum, the research findings offer an improved understanding of QST education research by previewing its trend, major contributors, intellectual structure and evolution, and future directions. The findings provide valuable insights for researchers, educators, and policymakers aiming to advance QST education.

Keywords: Bibliometric Analysis; Content Analysis; Education; Quantum Science and Technology (QST)

1.0 INTRODUCTION

The development of Quantum Physics (QP) at the beginning of the 20th century has overcome the limitations of classical Physics, which studies the motion of macroscopic objects with a deterministic worldview. Alternatively, QP enables the exploration of the world at a microscopic level, for instance, photons and electrons, with a probabilistic worldview [1]. The breakthrough of QP theory, namely the superposition of states, the probabilistic nature of quantum systems' evolution over time, and the connections of particles via entanglement have induced the first Quantum Revolution, also known as QR1.0 [2]. Moreover, its derived technological applications like lasers and solar cells [3], transistors and nuclear power plants [2], integrated circuits and optoelectronic devices with high computing power [4], and so on have severely reshaped our society.

Decades later, after scientists enabled quantum particles to interact individually, it sparked the inception of the second Quantum Revolution (QR2.0) at the end of the 1970s [2]. Advancements in controlling single quantum states and harnessing properties like superposition and entanglement have enabled rapid development of quantum-based technologies, including quantum computing, quantum information and communication, and quantum sensing and simulation. Hence, these destructive technological forces have dramatically overturned our present life, ranging from drug development in health sciences, cryptography in information technology, to enormous computational power for data sciences applications [4].

To promote technological breakthroughs and global dominance in the quantum field, leading nations across the globe have launched a series of national/transnational initiatives. This includes the U.K.'s National Quantum Technology Programme (NQTP) in 2013, Europe's Quantum Flagship Initiative in 2018, and the U.S.'s National Quantum Initiative (NQI) in 2018. As "the future is quantum", the sustainable development of Quantum Science and Technology (QST) in a nation is indispensable for nurturing competent quantum talents to fulfil the needs of quantum industries. Thus, all the national quantum initiatives have underscored educating the quantum-ready workforce.

The comprehensiveness of Europe's Quantum Flagship Initiative deserves more attention. Under this initiative, the Quantum Technology Education (QTEdu) project kicked off in 2020, intending to design a learning ecosystem to introduce and educate society about quantum technologies[1]. A year later, the project outlined the European Union's (EU) Competence Framework for Quantum Technologies (CFQT). The CFQT framework provides a vast landscape that maps the knowledge and skills required for the quantum workforce. It considers both theoretical and technological aspects and drafts broad outlines for eight significant domains: (1) concepts of quantum physics, (2) physical foundations of quantum technologies, (3) enabling technologies, (4) hardware for quantum computers and sensors, (5) quantum computing and simulation, (6) quantum sensors and metrology, (7) quantum communication, and (8) practical and soft skills. With six clearly defined proficiency levels for each domain, the EU's framework serves as a guidebook for various educational institutes to develop comprehensive QST programs.

Such a framework is an effective mechanism to cultivate a quantum-ready society and competent quantum workforce in enabling the future development of quantum industries in the region. It provides a vast landscape that maps the knowledge and skills required for quantum workforces to work in the quantum technologies industry. It considers both theoretical and technological aspects and drafts broad outlines for seven significant components, including concepts of quantum physics, the physical foundation of quantum technologies, enabling technologies, hardware for quantum computers and sensors, quantum computing and simulation, quantum sensors and metrology, quantum communication, and practical and soft skills. With six clearly defined proficiency levels for each competency component, EU's framework is deemed to be a guidebook for various levels of education and training institutes, ranging from primary school to professional training entities, to develop comprehensive and effective QST programs.

Having acknowledged the importance of QST education and the increased research interest in the subject over the last three decades, it is imperative to have a comprehensive overview of scholarly output in QST education. While previous studies have mapped the general landscape of Quantum Technology through bibliometric analysis, such as identifying the core

[1] https://qtedu.eu/why-qtedu-csa. Accessed 29 Apr. 2023

subfields of quantum communication [5], computation [6], technological realizations [2]. A comprehensive investigation dedicated specifically to the educational spectrum remains scarce. Existing reviews in education have been largely fragmented, focusing either on quantum physics learning difficulties at specific levels, for instance middle school students [4]. Or, they cover narrowly on a specific quantum technology application, such as quantum machine learning [7]. This present study bridges this gap by providing an up-to-date, full-spectrum analysis of QST education across all academic levels, distinguishing itself from broader technological reviews by focusing purely on human capital development and pedagogical evolution.

This study is different from past research by: first, it comprehensively examined the extant education research covering the full spectrum of QST across different levels of education; second, it applied an integrated approach (i.e., bibliometric and content analysis) to investigate both the quantitative and qualitative characteristics of the research constitutes on the subject; lastly, it retrieved bibliometric data systematically from the Scopus database. And this study is expected to contribute to QST education literature by answering the following research questions:

1. How has the scientific output in QST education research evolved regarding publications and citations from 1970 to 2022?
2. Who are the most prolific authors and countries publishing articles on QST education during this period?
3. What are the key research strands in QST education?
4. What is the intellectual structure of QST education research, how it has evolved over the years, and what are the emerging research directions in this domain?

Subsequently, insights from these answers enable the attainment of following three research objectives:

1. to illustrate the performance dynamics of research constituents on QST education.
2. to demonstrate the intellectual structure that lies within the extant QST education research.
3. to investigate the emerging and future research directions on QST education.

This study comprises of four sections. After briefly introducing the research topic, it elaborates on the research method and procedures applied in this study. Following this, results derived from the bibliometric analysis were discussed, before concluding the study.

2.0 METHODOLOGY

This study adopts an integrative mixed-methods research design, combining quantitative bibliometric analysis with qualitative content analysis. It begins with a bibliometric analysis to quantitatively analyze the performance of various research constitutes on QST education research, and network mapping to discourse the collaborative and intellectual structure in this research domain. It is then followed by a content analysis of the contextual information of key studies from each cluster[8]. In particular, the research subjects, methodologies applied, countries examined, and findings of the top cited studies from each thematic cluster are examined to have a collective understanding on the thematic structure of QST education research and identify “hot/blink spots” suitable for future research [9].

Given the unique advantages of bibliometric analysis in outlining the thorough knowledge structure and its time-spatial evolutionary pathway in a specific research field, an increasing number of studies have been conducted over the last few years on both quantum technologies and quantum physics/mechanics education. For instance, [10] applied scientometric analysis to examine publication activities of various countries in the field of quantum technologies, identify their positions in crucial sub-disciplines, and explore issues related to international cooperation based on publications indexed in the Web of Science database between 2000-

2016; [7] analyzed publication trends in Quantum Machine Learning by studying the Scopus and Web of Science (WoS) databases from 2014 to 2019; [4] examined the scientific outputs in quantum physics education research from 2000 to 2021 with a total of 1520 articles from peer-reviewed physics and science education journals indexed either in the Scopus or WoS database. [6] conducted a bibliometric analysis of research papers on quantum computation and quantum algorithms published between 1985 and 2020, indexed in the WoS database.

Despite that, a research gap exists in conducting an up-to-date survey of the scholarly outputs in quantum science and technology (QST) education research. Existing reviews have focused on specific subdomains of QST education, such as K-12 quantum physics [11] , undergraduate quantum computing [12], and quantum cryptography [13]. This presents a research gap for comprehensive QST education research that maps all the entire knowledge domain across all educational levels. Thus, the present study aims to address this gap by examining the performance and thematic structure of extant scientific output on the whole spectrum of QST education, spanning across all levels of education. This study has adopted an integrated approach to evaluate the research constituents, which comprises of total publications and citations, active researchers and countries, publishing avenues, collaboration patterns, the frequencies and co-occurrence of relevant keywords in the field. And the following sub-sections outline the steps taken to collect, process, and analyze the bibliographic data on QST education research.

2.1 Data Collection and Processing

The bibliometric data used for this study was collected in April 2023. A comprehensive search was performed in the Scopus database to retrieve academic publications on quantum science and technology (QST) education. The search queries were constructed with relevant keywords commonly used in the past QST education research, such as “quantum science”, “quantum technology", "quantum computing", "quantum mechanics", "quantum physics", and "education", combing with the usages of wildcards like "*", as well as binary operators including "AND" and "OR". Using these keywords, this research employed filtering to gather relevant publications by examining the article titles, abstracts, and author keywords. The filtering was limited to journal or conference papers published between 1970 and 2022. In addition, the language of publication was restricted to English only.

Table 1. below presented an overview of the search query and the resulting initial dataset size. The data was exported into CSV format to be ready for analysis via R’s Bibliometrix package and VOSviewer.

Table 1: Search Query and Dataset

Database	Search Query	Inclusion Criteria	Outcome
Scopus	(TITLE-ABS-KEY ("quantum physics") OR TITLE-ABS-KEY("quantum comput*") OR TITLE-ABS-KEY ("quantum mechanics") OR TITLE-ABS-KEY ("quantum science") OR TITLE-ABS-KEY ("quantum technolog*") OR TITLE-ABS-KEY ("quantum science and technology") OR TITLE-ABS-KEY ("quantum engineering") AND TITLE-ABS-KEY ("education")) AND (PUBYEAR>1970 AND PUBYEAR<2023) AND (DOCTYPE (ar) OR DOCTYPE (cp)) AND LANGUAGE (English)	1. Search terms included in the article’s title, keywords or abstract; 2. Articles published in peer-reviewed journals or conference proceedings; 3. Articles in the English language; 4. Articles published between 1970 and 2022	525

After eliminating eight unusable entries, including two duplicate and six incomplete ones, the bibliographic dataset comprised 517 articles. Then, the articles' titles and abstract were reviewed to retain only research focused on Quantum Science and Technology (QST) education. This yields a final corpus of 232 studies. The overview of the retained studies is presented in Table 2. The table revealed several noticeable features about the sampled bibliometric data: a) the annual growth rate of scientific output in this field was 8.93%, indicating a rapid increase in research activities in this field over the sampled period; b) the use of author keywords was prevalent, with a total of 547 unique terms found across the documents; c) the overall impact of these publications is reflected in the average of 8.466 citations per document, while the total number of 7,974 references indicates a broad and diverse knowledge base drawn upon by these studies.

Table 2: Overview of the Extracted Bibliometric Data from the Scopus Database

Category	Description	Results
Main Information	Timespan	1977:2022
	Journal Articles	142
	Conference Paper	90
	Annual Growth Rate %	8.93
	Average citations per document	8.466
	Total number of references	7974
	Total number of author keywords	547
Author	Number of authors	573
	Authors of single-authored docs	58
	Co-Authors per document	3.12
	International co-authorships %	9.052

2.2 Data Analysis

To explore more insights from the extracted bibliometric data, this study applied two primary techniques in conducting bibliometric analysis: a) performance analysis and b) science mapping. [14] explained that performance analysis evaluated the scientific output of a research domain through indicators, such as the total number of publications, and the total/average number of citations per article. Science mapping, on the other hand, visually represents the connections between various research constitutes, including authors, institutions, countries, and keywords, within a given research field using techniques such as co-citation analysis, co-authorship analysis, and co-word analysis [14]. When the above techniques are used in conjunction with network analysis, for instance, clustering (e.g., factor analysis) and visualization (e.g., overlaying temporal analysis), it can effectively illustrate both the bibliometric and intellectual structure of the research field [15].

To ensure the robustness of the performance analysis, the researchers utilized the fractionalized counting method to evaluate author productivity. Unlike standard counting which assigns a full credit to every co-author, fractionalized counting assigns a mathematically proportional fraction of credit to each co-author, ensuring that the aggregated total exactly matches the total number of sampled publications, thereby providing a more precise and balanced bibliometric measurement [16]. For science mapping, VOSviewer parameters were strictly defined. Co-citation analysis was thresholded at a minimum of 2 citations per cited reference, and co-word analysis was filtered to include only keywords with at least two co-occurrences, ensuring that only meaningful conceptual overlaps were mapped.

A detailed breakdown of the data analysis performed is presented in Table 3. To perform the bibliometric analysis, the R's Bibliometrix package was utilized. In addition, we have utilized VOSviewer to generate visualizations of the science mapping results.

Table 3: Methods and Tools of Bibliometric Analysis

Method	Unit of analysis	Tool	Research question
Descriptive Analysis	Articles	R's Bibliometrix package	RQ1: scientific output trend from 1970 to 2022
Performance analysis	Articles	R's Bibliometrix package	RQ2: performance of various research constituents (e.g., authors, institutions, countries).
Co-authorship analysis	Author, Affiliations	R's Bibliometrix package	RQ2: pattern of research collaborations
Citation Analysis	Articles	VOSviewer	RQ3: what are the influential studies in this area?
Co-citation analysis	Articles	R's Bibliometrix package	RQ4: What is the intellectual structure of QST education research?
Co-word Overlay visualization	Keywords	VOSviewer	RQ4: How does the research focus on QST education evolve?

To complement the quantitative bibliographic analysis with qualitative insights, a content analysis was conducted later. It involved extracting the most influential studies from the clusters generated by the VOSviewer co-word analysis, synthesizes the thematic developments, and contextualizes the findings. Detailed qualitative insights generated from the content anlaysis is presented in Section 3.6.

3.0 RESULTS AND DISCUSSION

3.1 Performance Analysis

The sample bibliometric data used in this study included 142 journal articles (61.2%) and 90 conference papers (38.8%). More specifically, it comprised 32 sources authored by 573 individuals affiliated with 212 institutions across 34 countries. In total, there were 7,974 cited references. Figure 1 illustrates publication activities in QST education research. The earliest article recorded in the Scopus database dated back to 1977, and the number of publications experienced steady growth from 1990 to 2014, indicating a consistent increase in the number of articles published. Notably, there has been a significant growth in scholarly article production over the last decade, ranging from 14 publications in 2017 to 41 in 2020.

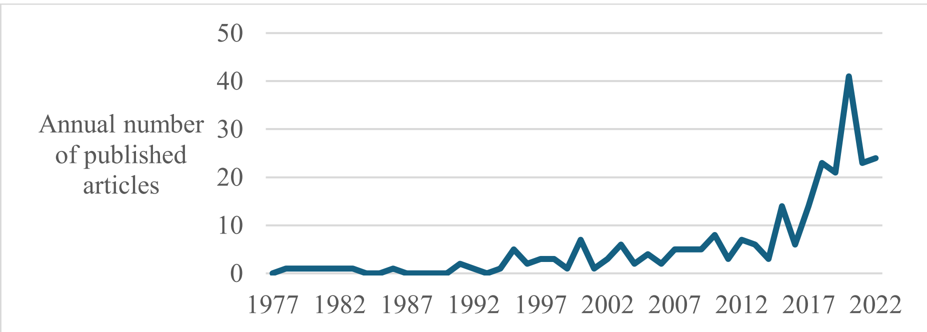

Figure 1: Scientific Production Over Time

The growth of the scientific body and the time-dependent impact of publications in QST education can be examined by the yearly average citations of the manuscripts published in a particular year [17]. Figure 2 revealed that the mean total citations fluctuated across the sampled period, with varying citation peaks. It ranged from an average of 4.03 citations per document in 2011 to 2.64 in 2019, indicating both the temporal variations in QST education research impact and the dynamic expansion of scientific outputs in the field. In particular, the recent period has witnessed a relatively high average citation count ranging from 2.64 in 2019 to 4.03 in 2011, suggesting a notable impact of the publications during those years and the growth of research activities in the field. Hence these findings have echoed Figure 1, which presented a rapid growth of scientific production over the last decade.

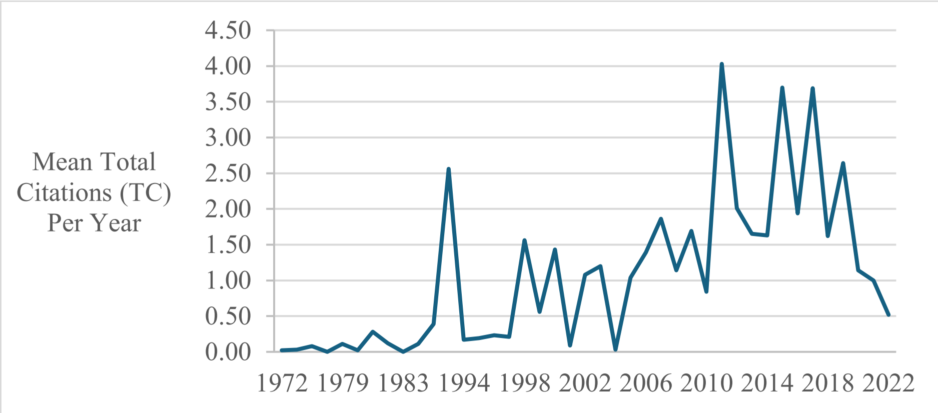

Figure 2: Average Citations Over Time

This significant surge in scholarly article production and citations implies the rising research interests on QST education. This phenomenon can be attributed to the major international policy milestones pertaining to QST development occured over the last few year. The exponential growth aligns perfectly with the launch of massive transnational funding initiatives designed to accelerate the second quantum revolution. Most notably, the launch of UK's National Quantum Technology Programme (NQTP) in 2013, the enactment of the U.S. National Quantum Initiative (NQI) Act in 2018, and the launch of Europe's Quantum Flagship Initiative in the same year. Because these policies explicitly mandate the expansion of researchers, educators, and a trained quantum workforce to secure technological dominance, they have acted as direct catalysts for the rapid expansion of QST education research globally.

Table 4 unveiled the top 10 prolific authors in QST education research measured in terms of the total and fractionalized number of published studies. As many scientific outputs were co-authored, the fractionalized count has been introduced to account for each author's relative contribution to a single study. In contrast with assigning each contributing author one credit, the fractionalized count assigns a fraction of the credit to each co-author for publication. Since fractional counting assures the aggregated total counts are the same as the total number of sampled publications, it is perceived to be a relatively balanced, consistent and precise bibliometric measurement [18]. According to the table, Singh C. emerged as the most productive author, with 12 articles published, representing a significant contribution of 4.86 fractionalized articles. This was followed by Marshman's 8 publications with 3.5 fractionalized counts. Though Bitzenbauer was ranked 5th in total counting after Finkelstein and Malgieri, based on his fractionalized count of 3.45, Bitzenbauer's research productivity performance has been elevated to third place.

To evaluate the contributions of individual countries in the field of QST education research, Table 5 presents an overview of the top 10 countries with the highest scientific outputs. This metric aims at quantifying the representation of authors from various countries in academic articles. Specifically, for each article, if multiple authors are affiliated with different countries, the count of appearances for each respective country is increased by 1. Table 5 shows that the USA has demonstrated a prominent role in the global landscape of QST education research, boasting an impressive publication count of 310 studies. Following this, significant contributions have also been observed from Italy and the U.K.

Table 4: Performance Analysis: Top 10 productive authors

Authors	Articles	Articles Fractionalized
SINGH C	12	4.86
MARSHMAN E	8	3.50
FINKELSTEIN ND	6	2.53
MALGIERI M	6	2.07
BITZENBAUER P	5	3.45
MICHELINI M	5	1.32
BAILY C	4	2.00
LEWANDOWSKI HJ	4	0.89
PASSANTE G	4	1.03
DIDIŞ N	3	1.00

Table 5: Performance Analysis: Top 10 countries in scientific production

Countries	No. of Articles
USA	310
Italy	57
U.K.	41
Netherlands	37
Australia	36
China	25
Germany	19
Norway	19
Greece	16
Denmark	14

While Table 5 demonstrates the prominent role of nations like the USA, Italy, and the U.K., this distribution exposes a stark geographic imbalance, highlighting a severe underrepresentation of the Global South in QST education research. The dominant contributors consist mainly of developed nations in North America and Europe, with China as the primary exception. This descriptive data points to a critical lack of infrastructural and educational investment in developing regions, threatening to create a 'quantum divide' in the future global workforce [19]. Addressing this imbalance is critical. Emerging initiatives, such as 'Quantum Leap Africa' launched by the African Institute for Mathematical Sciences, aim to mobilize youth and position the continent within the quantum landscape [20]. Future QST education research must prioritize these regions to ensure equitable geographic representation and global workforce readiness.

In the context of publishing avenues for education research, Table 6 provided an overview of the top 10 journals/conference proceedings based on the total number of studies published. Among these sources, the European Journal of Physics emerged as the leading publishing outlet, demonstrating its prominence in disseminating research within the field. Additionally, the Journal of Chemical Education, AIP Conference Proceedings, and Physical Review Physics Education Research were also notable contributors to further enriching the scholarly discourse. The significance of conference proceedings in the QST education research landscape is worth noting, as evidenced by their presence in 5 out of the top 10 publishing avenues. This observation aligned with the findings of [21], suggesting that cutting-edge developments in fields like computer science and engineering, such as QST education in this case, often find initial expression in conference proceedings. In addition, it also indicated the emergence of new trends and novel ideas before their subsequent publication in journals.

Table 6: Performance Analysis: Top 10 publishing sources

Sources	**Articles**
European Journal of Physics	25
Journal of Chemical Education	11
AIP Conference Proceedings	10
Physical Review Physics Education Research	9
Proceedings of SPIE – The International Society for Optical Engineering	9
ASEE Annual Conference and Exposition, Conference Proceedings	8
Science and Education	8
Journal of Physics: Conference Series	7
Proceedings - 2022 IEEE International Conference on Quantum Computing and Engineering (QCE 2022)	7
Physics (Switzerland)	5

3.2 Scientific Mapping

Apart from exploring the performance of various scientific constituents and examining the performance of various scientific constituents, it is also compelling to investigate the patterns of collaborative research efforts across different countries and institutions via scientific mapping. Due to the advanced scientific concepts underlying QST education and its rapidly evolving nature, it becomes enormously challenging for an individual researcher to investigate the subject thoroughly. Therefore, collaborative research becomes an effective approach to pool complementing resources and expertise across the globe to yield comprehensive pedagogical methods and instruments for delivering high-quality QST education [22].

By analyzing key author attributes such as institutional affiliations and countries, co-authorship analysis measures intellectual collaboration among scholars. Furthermore, it reveals the research focus among researchers within a region and previews future research potentials for underserved regions. Moreover, exploring co-authorship networks in the research domain is a valuable resource for aspiring scholars aiming to establish meaningful connections and engage in fruitful collaborations within the field [14]. By harnessing the potential of these networks, prospective scholars can tap into a wealth of knowledge and collaborative opportunities, contributing to their growth and fostering advancements within the research domain.

In this study, the co-authorship analysis was performed on both national and institutional levels. Nodes were used to represent the affiliated institutions or countries, while links were applied as proxies for co-authorships. In addition, the node's size corresponded to the number of papers originating from the respective institution or country. In contrast, the thickness of interconnecting lines reflected the number of co-authored papers between individual authors. Figure 3 showcased the intellectual interactions at the national level. Notably, the USA-based research institutions emerged as the primary driver fostering cross-nation collaborative research endeavours in QST education, particularly with the U.K.-based counterparts. To further explore the dynamics at the institutional level, Figure 4 highlights the exceptional contributions of the University of Colorado and the University of Pittsburgh in fostering scholarly collaborations in USA and global QST education research communities.

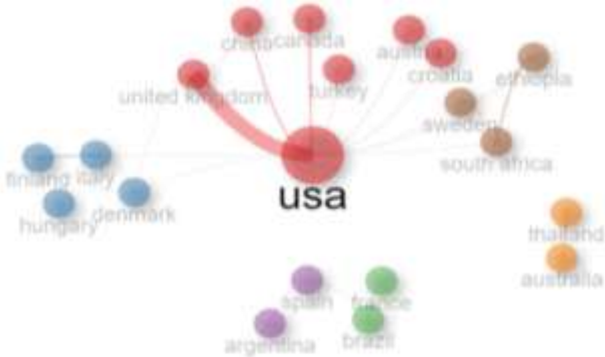

Figure 3: National co-authorship analysis

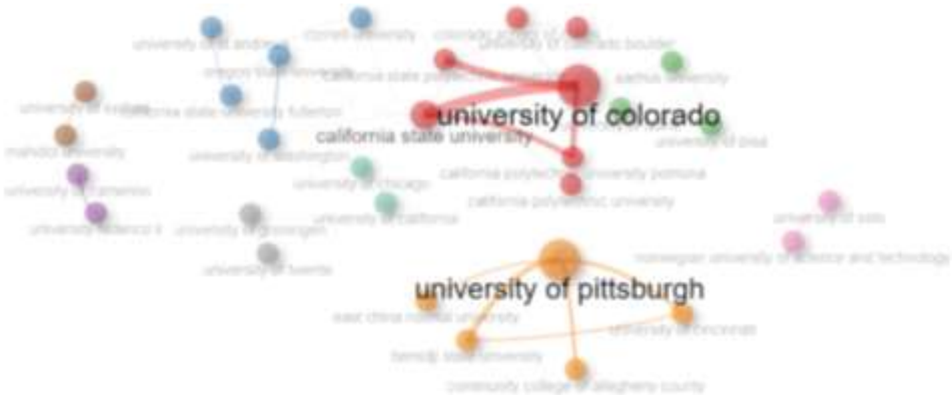

Figure 4: Institutional Co-authorship analysis

Citation analysis was applied in this study to investigate influential publications and authors in QST education research. Global Citations (GC) and Local Citations (LC) metrics were utilized to examine the relative importance of the publications and authors. GC reflected the frequency of citations a publication has received from studies across various databases, encompassing diverse disciplines and research domains [23]. In contrast, LC quantified the citations within the sampled bibliometric collection. Table 7 presents the top 10 globally cited QST education research. The table revealed that Johnston et al. [24]'s "Student difficulties in learning quantum mechanics" has received the highest number of GC (118), averaging 4.54 citations per year. This is followed by Singh & Marshman [25]'s "Review of student difficulties in upper-level quantum mechanics" with 106 GC and an impressive citation rate of 11.78 per year. Following this, Krijtenburg-Lewerissa et al. [12]'s "Insights into teaching quantum mechanics in Secondary and Lower undergraduate education" has secured third place with 95 GC and an average of 13.57 citations per year.

Regarding influential authors in the research field, Table 8 showcased the top 10 authors who have received the highest local and global citations. Based on the analysis, Singh, C. emerged as the most globally cited author, reflecting his significant contributions to the QST education research domain. Passante, G. received the highest local citations, highlighting her dominating influence within the sampled bibliometric collection. Other authors such as Marshman E, Johnston ID, Zhu G, and Finkelstein ND have also received notable local and global citations, indicating their relative influences in the field.

Table 7: Citation Analysis: Top 10 global cited articles

Paper	Global Citations (GC)	GC per Year
[24]	118	4.54
[25]	106	11.78
[12]	95	13.57
[26]	88	5.18
[27]	87	6.69
[28]	82	2.56
[29]	76	3.62
[30]	75	5.00
[31]	74	6.17
[32]	71	3.23

Table 8: Citation analysis: Top 10 local and global cited authors

Author	Local Citations	Author	Global Citations
Passante G	144	Singh C	599
Singh C	112	Marshman E	312
Marshman E	79	Johnston ID	218
Pollock S	66	Zhu G	182
Sadaghiani H	52	Passante G	176
Pollock SJ	49	Finkelstein ND	156
Finkelstein ND	46	Baily C	150
Bungum B	40	Hadzidaki P	145
Baldwin S	38	Brinkman A	129
Evason C	38	Krijtenburg-Lewerissa K	129

To comprehend the intellectual structure of QST education research, this study utilized co-citation analysis, which served as a science mapping technique. This approach operated on the premise that publications cited together possess thematic similarities. In other words, if two publications are cited together in the reference list of another publication, they are deemed connected and shall share common underlying intellectual themes [14]. The advantages of employing co-citation analysis are twofold. Firstly, it facilitates the identification of influential publications within the field. By examining the co-citation frequency, researchers can pinpoint the most impactful work that has shaped the domain's development. More importantly, it enables the discovery of thematic clusters. These clusters emerge from the connections established among cited publications, offering a comprehensive overview of the major themes present in the field [14].

Figure 5 presents the co-citation analysis of cited references to investigate the intellectual structure of QST education research. From the sampled 7974 cited references, the co-citation analysis managed to generate a set of 50 references by employing the threshold of 2 times, which means the minimum number of citations of a cited reference was 2. As depicted in the figure, two clusters emerged in the co-citation analysis. Specifically, the first cluster (red) focused on the perspective of teaching quantum mechanics. For instance, many cited references were relevant to developing quantum mechanics conceptual education tools [7], [30], [33] and teaching strategies [34], [35], [36]. The second cluster (blue) focused on understanding the difficulties [25], [31], [37], [38] and the development of curriculum content for quantum mechanics education [39], [40].

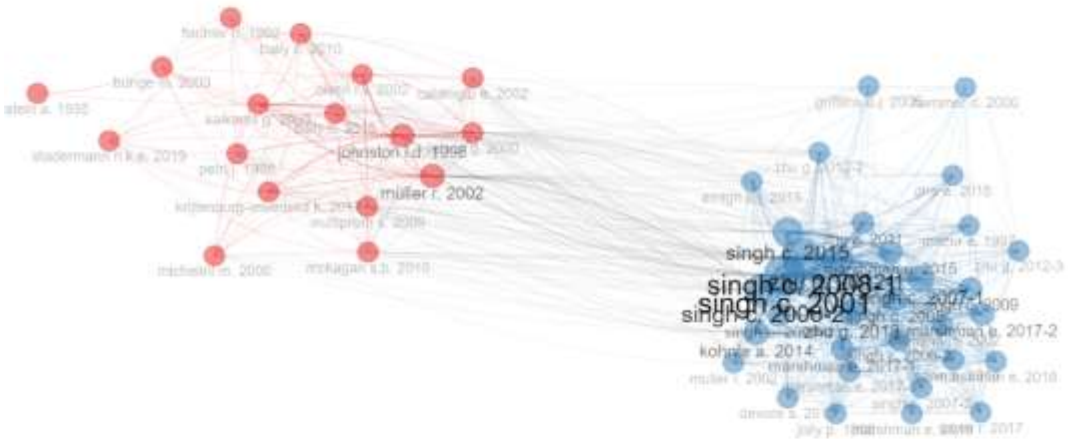

Figure 5: Co-Citation Analysis on Cited References

To delve further into the clusters identified from the previous co-citation analysis, we have proceeded with a co-word analysis on the co-occurrence of keywords. The co-word analysis examines the sampled studies' actual content to derive the field's thematic structure. In particular, the unit of analysis for co-word analysis comprises both author and index keywords of the sampled studies. When the keywords are frequently used together, the commonalities extracted from these keywords are used to derive themes for each cluster. Thus, co-word analysis is expected to complement co-citation analysis to provide a more enriched comprehension of a research domain’s conceptual structure [41].

The co-word analysis has employed VOSviewer to map the co-occurrence of keywords, and the visualized network is illustrated in Figure 6. In this diagram, the nodes represent the keywords used in the sampled QST education research. The node's size corresponds to the frequency of its occurrence, while the connecting line indicates two terms that have been labelled as keywords in the same article. Furthermore, the thickness of the links between nodes reflects the number of co-occurrences. By setting a threshold of at least two co-occurrences [42], the analysis has filtered out 33 mostly used keywords from a total of 349 unique terms.

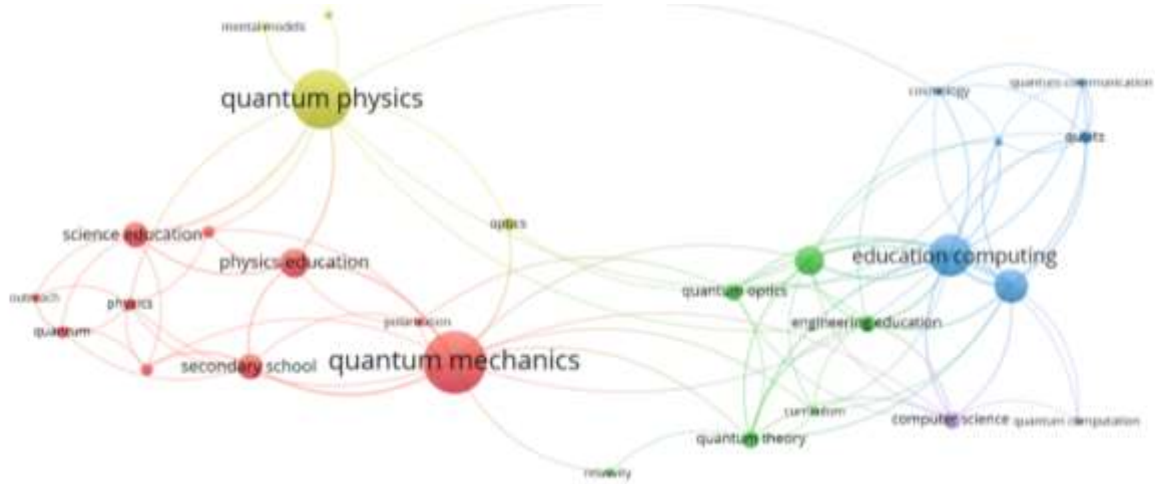

Figure 6: Co-words Analysis on Co-occurrence of Keywords

The relatedness of the co-occurred keywords has revealed five strands in QST education research, represented by five distinct colored clusters. For each cluster, the co-occurring keywords are further analyzed in the context of the sampled QST studies. Consequently, we managed to derive a collective theme for each cluster to reflect the relatedness and commonalities of these interlinked keywords (refer to Table 9). Contrasting with the two general clusters that emerged from the co-citation analysis (refer to Figure 5), the co-word analysis provides a more detailed conceptual breakdown of the extant QST education research.

In particular, the red-colored cluster focuses on “Quantum physics education approach”, represented by common keywords like “quantum mechanics”, “physics education”, “science education”, and “secondary school”. The green one emphasizes “Quantum engineering and computing education”, denoted by frequent keywords such as “quantum computing”, “engineering education”, “quantum theory”, and “quantum optics”. The blue cluster is on “leveraging educational computing for learning quantum computing and communication”, evidenced by frequently used keywords such as “education computing”, “quantum computers”, “qubits”, and “quantum entanglement”. Another cluster is centered on the idea of “Quantum physics educational strategies”, denoted by frequent keywords like "quantum physics", "mental models”, and “pre-service teachers”. Finally, the cluster on “Integrating quantum computing into computer science education” is highlighted in purple color, indicated by the wide usage of “quantum computing” and “computer science”.

Table 9: Cluster and Keywords

Cluster	Color	Keywords	Theme
1	Red	Quantum mechanics; physics education; secondary school; science education; physics; quantum; polarization; outreach; nature of science; higher education	Quantum physics education approach
2	Green	Quantum computing; engineering education; quantum theory; quantum optics; curriculum relativity	Quantum engineering and computing education
3	Blue	education computing; quantum computers; quantum entanglement; quantum communication; qubits; cosmology;	Leveraging educational computing for learning quantum computing and communication
4	Yellow	Quantum physics; optics; mental models; pre-service teachers	Quantum physics educational strategies
5	Purple	Computer science; quantum computation	Integrating quantum computation into computer science education

While the thematic clustering is coherent, notable conceptual overlaps exist within the network map. Specifically, the term “quantum computing” acts as a bridge, appearing dominantly across multiple strands (Clusters 2, 3, and 5). This overlap is not a flaw in the clustering analysis but an accurate reflection of the inherently interdisciplinary nature of quantum technologies. Quantum computing cannot be isolated; it intrinsically bridges classical computer science, engineering education, and advanced physics [43].

Co-word analysis also enables a preview of the temporal evolution of research themes in QST education [41]. By incorporating information on publication time, the overlay visualization of the co-occurrence network identifies the development trajectories of research foci in the field. Moreover, it predicts novel research directions for QST education. Figure 7 demonstrates the co-occurrence of keywords from 2012 to 2020 using temporal overlaying visualization techniques. In particular, each node is associated with a color corresponding to its average publication year [44].

As the figure depicts, the research focus has gradually evolved from general and theoretical educational content such as “quantum theory”, “computer science”, and “engineering education" to explore practical pedagogical approaches for a specialized area, including "quantum mechanics" and "education computing". Furthermore, novel research areas emerged from this field concerning developing educational initiatives (e.g., "outreach" and "secondary school") and teaching methods (e.g., "mental model") for complex quantum subjects (e.g., "quantum computing", "optics", "qubits", and "polarization"). This shift can be attributed to the recognition of vast applications of quantum computing and the growing industry demand for quantum computing expertise [45]. Overall, the co-word analysis revealed distinct thematic strands and demonstrated dynamic changes in research focus, highlighting the significance of quantum computing education in response to emerging applications and market demand.

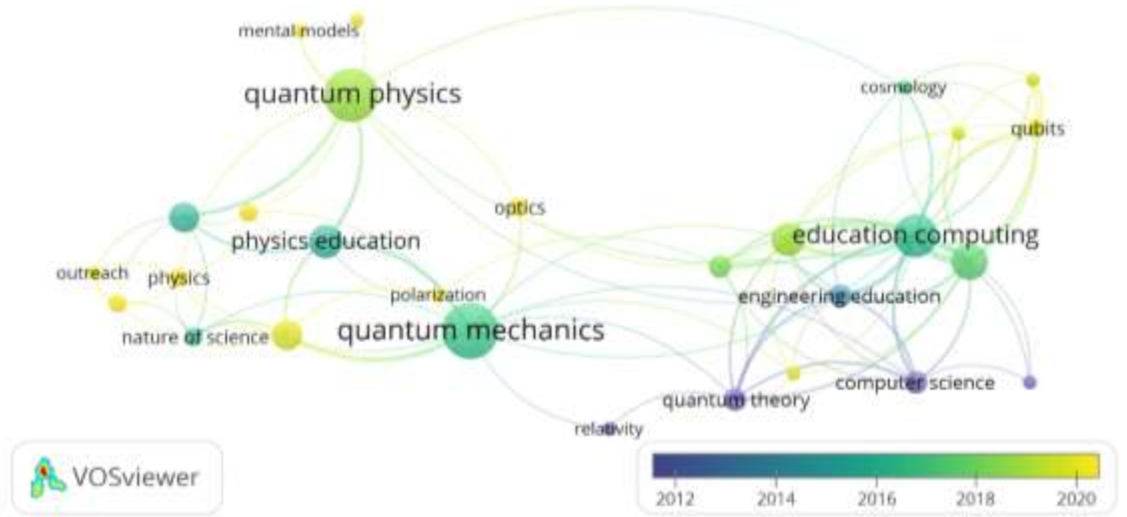

Figure 7: Temporal Overlaying Visualization of Co-occurrence Network

3.3 Content Analysis

To uncover more insights from the identified clusters, this study has continued with a content analysis of key studies derived from the five distinct clusters identified from the co-word occurrence network map (see Figure 6 and Table 9). In doing so, it reviewed the research areas, methodologies applied, research subjects, findings, and implications of the influential studies in each cluster to better comprehend the evolving intellectual structure of QST education between 1977 and 2022. Table 10 (Appendix) summarizes the primary references reviewed under each cluster.

Cluster 1: Quantum Physics Education Approach

Studies in this cluster focus on the global efforts in scrutinizing effective educational approaches for better understanding of quantum physics. Having acknowledged the complexity of the subject, it is crucial for secondary school to introduce core quantum theories into its curriculum to better prepare students for advanced quantum physics discourse in the university [46]. And to attain effective quantum education in secondary school, extant studies have advocated to embrace the inherent complexity of the quantum physics through philosophical/epistemological discourse. For instance, [47] postulated that epistemological discussions about the underlying nature of quantum physics allow secondary school students to productively synthesize the contradictory concepts, leading to a more robust understanding.

Similarly, in the case of Norwegian secondary school, [48] underscored the importance of integrating philosophical reflections of quantum theory into teaching activities. Furthermore, clear and explicate communications of learning outcomes plays a pivotal role in navigating students' effectively understandings of such intricate subject. Another valuable educational approach recommended is to foster peer interactions during students' learning process. [49]

demonstrated that university undergraduate students in China achieved a deeper grasp of quantum physics concepts via peer learning.

Cluster 2: Quantum Engineering and Computing Education
In the realm of quantum engineering and computing education, recent studies have offered insights on pedagogical approaches for effective learning experiences, particularly in developed countries like the USA. These studies have underscored the critical role of integrating practical applications into quantum computing education. This approach will bridge students' theoretical and practical understanding gap, bringing in effective quantum engineering and computing learning. [50] advocated the application of software-driven teaching approach for quantum computing in university's undergraduate education. It emphasized integrating programming practices and capstone projects into teaching/learning, enabling students to leverage practical applications to obtain deeper understanding of the real-world scenarios of quantum computing principles.

[51] added that Naive Measurement Probability and Virtual Quantum Computer simulations are two effective practical tools students can rely on to develop intuition and understanding of quantum computing theories. As for high-school students, the complexities of quantum theories can be overwhelming for comprehension. [52] suggested to incorporate optics-based wave mechanics into theoretical quantum computing teaching, enabling students to leverage their prior knowledge on light and wave behaviors for better grasp of abstract quantum computing principles.

Cluster 3: Leveraging Educational Computing for Learning Quantum Computing and Communication
Despite the burgeoning interests in quantum computing and communication, its theoretical complexities have presented severe challenges for educators. To facilitate effective learning, past studies has proposed to employ educational computing to enable students learning abstract quantum theories via interactive simulations and visualization [53]. Furthermore, [53] have stressed importance of learning path for K-12 learners. Students who follow the superposition-quantum states-entanglement-measurement-reversibility studying trajectory can gain better understanding of the major building blocks of quantum mechanics.

As for quantum communication, [54] suggested to incorporate Diffie-Hellman based key agreement protocol into educational computation framework. Learning quantum cryptography through interactive simulations and exercises allows students to gain practical understanding on how quantum theories work and their implications on secured communication.

Cluster 4: Quantum Physics Teaching Strategies
Another strand of studies has focused on the teaching strategies for enhancing students' quantum physics learning experiences. The sampled studies have revealed three major strategies, including incorporation of group-based interactive discussions, application of practical teaching tools, and understanding of students' mental models. First, [55] highlighted the effectiveness of small-group discussions among pre-university students in fostering their understanding on abstract and counterintuitive quantum physics dilemmas, such as wave-particle duality and Schrödinger's cat. Bungum et al. explained that peer-based interactive discussions enable students to clarify theoretical complexities through exchange of constructive thoughts, which helped them obtain deeper grasp of the knowledge.

Furthermore, it is crucial to ensure the implementation of teaching concept is properly aligned with teaching materials to ensure quality quantum physics education. In particular, Bitzenbauer underscored the effectiveness of hands-on based teaching content, through integrating interactive experiments, video explanations, updated practical quantum applications, and instructor' teaching manual, in reinforcing active quantum physics learning [56]. Lastly, [57] highlighted the importance of understanding students' mental model in comprehending quantum physics. In doing so, it enables educators to employ suitable teaching concepts and materials to help students avoid misconceptions and attain better understanding of the underlying quantum theories and the related phenomena.

Cluster 5: Integrating Quantum Computation into Computer Science Education
The last area emerged from sampled studies is related to the call for blending quantum computation into classical computer science education. [58] postulated that an interdisciplinary approach will be effective. Stephney suggested students major in any science field for their undergraduate degree, then continue to pursue advanced studies in post-classical computing (with the inclusion of quantum computing). This approach will not only enable students to develop a broader knowledge base, but also to equip them with adequate skills to comprehend the abstract and complex quantum computing concepts. Furthermore, [59] advocated to introduce quantum computation as a supplementary topic for advanced computer science course in undergraduate education. Main et al. added that to foster better understanding it is crucial for students to have a firm grasp of advanced matrix techniques, which enables them to simulate complex quantum phenomena (e.g. entanglement) through matrix representations (e.g. Kronecker product).

Furthermore, a systematic examination of these clusters reveals distinct pedagogical approaches tailored to specific educational levels:

- K-12 and Secondary Education: Research emphasizes conceptual visualization, philosophical interpretations, and real-world analogies (e.g., games and simulations) to bypass the barrier of advanced mathematical formalism.
- Undergraduate and Graduate Education: The focus shifts toward integrating rigorous mathematical frameworks (e.g., matrix techniques), practical programming, and engineering capstone projects to build functional, industry-ready skills.

4.0 CONCLUSION

This study has employed bibliometric analysis to capture the performance of scholarly output on QST education research and depicted the evolving conceptual structure of the field. The study's findings revealed a significant growth in the scientific production of QST education research over the past two decades, with a notable increase in publications. This indicated the growing interest and importance of QST education in academia. The study has also identified the most prolific authors and countries in terms of publication counts, with Singh C. and the U.S. emerging as leading contributors in the field.

The study also highlighted the role of publishing avenues in disseminating research in the field. The European Journal of Physics was identified as the leading outlet for publishing research in this area, followed by other notable journals and conference proceedings. The presence of conference proceedings among the top publishing venues indicated the importance of academic conferences in showcasing new research ideas and findings in QST education.
Additionally, the study examined the patterns of collaboration among scholars. It revealed strong collaborations among research institutions in the U.S. and the U.K., emphasizing the importance of international collaborations in advancing the research domain. The University of Colorado and University of Pittsburgh have emerged as the pivotal driving force fostering collaborative research efforts at both domestic and international levels.

Furthermore, the study explored the intellectual structure and research themes in QST education research. The analysis revealed five research clusters among sampled studies and previewed emerging research focuses on the field, such as quantum computing and quantum communication education. Research in this area is expected to yield a significant impact on QST industry and continue to reshape the quantum future. As an implication, it indicates that this domain of quantum education could be a promising avenue for future research exploration.

The content analysis of the five research clusters has highlighted the growing importance of constructive pedagogical approaches for QST education. In particular, the emphasis has shifted from conveying simplified quantum concepts to fostering deeper comprehension of quantum complexities through innovative teaching concepts and practical teaching materials. This includes promoting peer-based interactive discussions in the class, integrating hands-on experiments in the teaching process, and utilizing educational computing tools like simulation and visualization to demonstrate quantum phenomena. Furthermore, the studies have also underscored the indispensable role of philosophical discourse and mental models in facilitating students' productive learning on abstract quantum concepts and counter-intuitive quantum phenomena. Lastly, it is necessary to incorporate the latest practical applications of quantum computation into classic physics and computer science courses to equip students with the essential skills and knowledge required in this rapidly evolving field.

The research findings provide strong evidence that QST education research is experiencing a period of rapid and critical expansion. This growth is not merely organic but is heavily driven by recent transnational policy milestones, such as the U.S. NQI Act and the EU Quantum Flagship, that prioritize workforce development. However, the performance analysis reveals a significant geographic disparity, with the Global North heavily dominating the discourse while the Global South remains marginalized. Bridging this 'quantum divide' must be a priority for global policymakers.

Overall, this study contributed to the understanding of the current state of QST education research and provided insights into its trends, influential contributors, and conceptual evolution. The findings can serve as valuable resources for researchers, educators, and policymakers interested in furthering the development of QST education and its integration into various educational levels and domains. The intellectual structure of the field demonstrates that effective QST education requires highly interdisciplinary, constructive pedagogical approaches tailored by educational level. While secondary education benefits most from philosophical discourse and visual simulations that avoid mathematical barriers, higher education must integrate practical programming and advanced matrix techniques into computer science and engineering curricula. Ultimately, the insights derived from this study highlight the urgent need for continued, equitable, and cross-disciplinary collaboration to shape an inclusive and highly skilled quantum-ready workforce for the future.

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CONFLICT OF INTEREST

Competing interests: No relevant disclosures.

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APPENDIX

Table 10: Clusters and Selected Key Studies

Cluster	Study	Sub-theme	Methodology	Education	Findings
Red:Quantum physics education approach	[47]	Instructional design	Experiment	upper secondary school (Italy)	Embracing the complexity of quantum physics through epistemological discourse, rather than oversimplification of the content, enables the productive syntheses of students.
	[48]	Teaching and Learning process	Design-based research	upper secondary school (Norway)	To foster secondary students' effective understanding on quantum physics, it is vital: a) to understand qualitative aspects of the subject by aligning innovative teaching activities with philosophical and epistemological reflections, b) to explicitly express the expectations for students by a proper teaching sources-goals-assessment alignment.
	[46]	Students' comprehension	Qualitative analysis	Undergraduate (Turkey)	University students suffer difficulties in comprehending quantum mechanics, which can be attributed to: a) the absence of quantum physics content in the high school syllabus, b) the premature requirement on advanced mathematical skills without a solid conceptual understanding of quantum theory.
	[49]	Educational method	Experiment	Undergraduate (China)	Students' conceptual understandings of quantum physics improved dramatically via peer interaction educational approach.
Green: Quantum engineering and computing education	[50]	Teaching approach	Case study	Undergraduate (USA)	The software-driven teaching approach enables students to absorb complex quantum computational theory via programming practices and capstone projects.
	[51]	Student reasoning	Qualitative analysis	Undergraduate (USA)	Students mostly apply Naïve Measurement Probability and/or Virtual Quantum Computer strategy to understand quantum computing concepts.
	[52]	Course design	Case study	High school (USA)	Integrating optics-based wave mechanics into quantum computing courses helps high school students better understand quantum concepts.
Blue: Leveraging educational computing for learning quantum computing and communication	[53]	Educational content	Qualitative analysis	K–12	Young learners can follow the learning trajectory of Superposition-Quantum State- Entanglement-Measurement- Reversibility to study quantum computing without in-depth technical foundation.
	[54]	Educational computing	Conceptual	China	Developing a Diffie-Hellman based key agreement protocol to improve the security of quantum cryptosystem.
Yellow: Quantum	[55]	Group discussions	Hybrid approach	upper secondary school (USA)	Small group-based productive discussions enhance secondary school students' philosophical comprehension of quantum physics. The peer-interactive discourse enables students to exchange ideas and motivates

physics teaching strategies					new inquiries about complex quantum theories, thereby enhancing their grasp of the concepts.
	[56]	Teaching materials	Design-based research	Secondary school (Germany)	A new teaching sequence, including theoretical concepts and experimental activities, is designed to effectively teach quantum optics in secondary school.
	[57]	Mental models	Quantitative analysis	Students and other professions (Germany)	The disposition of people's understanding of quantum physics can be assessed through two dimensions: (i) Functional Fidelity, which measures the functional representation of quantum phenomenon; (ii) Gestalt Fidelity, which assesses the visual representation accuracy of real-world scenarios. The functional aspects of mental models play a more predominant role in the comprehension of quantum physics, indicated by a higher functionality score.
Purple: Integrating quantum computation into computer science education	[59]	Teaching content	Experiment	Undergraduate (USA)	Quantum computing can be introduced into the CS2 class as a supplement topic. However, advanced matrix techniques shall be introduced to students to enable them to simulate quantum games with matrix representation.
	[58]	Teaching content	Conceptual	NA	Applying an interdisciplinary approach to fuse science with computer science (CS), is an effective design for post-classical CS education. In doing so, a student would need to first major in any science field before taking CS courses to pursue a master's education.