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Article

Quantum Physics Education Research over the Last Two Decades: A Bibliometric Analysis

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Abstract: Quantum physics is an essential field of science education research, which reflects the high relevance of research on quantum physics and its technologies all around the globe. In this paper, we report on a bibliometric analysis of the science education research community's scientific output in the area of quantum physics in the period from 2000 to 2021. A total of 1520 articles published in peer-reviewed physics and science education journals were retrieved from Web of Science and Scopus databases to conduct bibliometric analysis. This study aims to provide an overview of quantum physics education research in terms of scientific production, preferred publication venues, most involved researchers and countries (including collaborations), and research topics. The main findings point to a continuous increase in research output in the field of quantum physics education over the last two decades. Furthermore, they indicate a shift regarding the research foci. While formerly mainly papers on the teaching of quantum physics content were published, recently, an increase in the relevancy of empirical studies on the teaching and learning of quantum physics can be observed.

Keywords: quantum physics; bibliometric analysis; science education

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1. Introduction

In the past, the first quantum revolution has influenced our society "with the development of integrated circuits and optoelectronic devices [...] through high-performance computing, transoceanic communication, high-speed Internet and medical devices" [1]. Today, the second quantum revolution is underway [2]: In the upcoming years, products and applications based on the exploitation of quantum principles such as superposition or entanglement will emerge in many different ways [3]. Second generation quantum technologies, also referred to as *Quantum technologies 2.0*, such as quantum computing, quantum communication, quantum sensing or quantum simulation, are said to have significant disruptive potential: "They hold the promise to affect dramatically our life overturning everything, from drug development, to cryptography, to data science and Artificial Intelligence" ([4], p. 2). In short: "The future is quantum" (https://qt.eu/, accessed on 28 October 2021).

Besides scientific research, the commercialisation of quantum technologies requires training programmes for the future quantum workforce [5]. Moreover, students at high schools and the general public should also be educated in quantum physics [4]: On the one hand, because quantum physics is, among other things, particularly suitable for epistemological reflection [6,7] or for discussing the role of models in science [8]. On the other hand, to create awareness among the public for the importance of modern quantum technologies for their own lives [9] today and in the future. Last but not least, a mystification of quantum physics [10], which is not only widespread in popular science literature, can be tackled in this way.

However, learning quantum physics and teaching it is particularly challenging for various reasons: for instance, because students lack the mathematical background to delve into quantum formalism or because of quantum physical effects contradicting classical models that students are used to thinking in [11]. Consequently, learning quantum physics requires a radical conceptual change [12]—a "knowledge reboost" [13]. Quantum physics education research, among other things, aims at identifying and developing ways to initiate such a conceptual change towards quantum thinking.

Today, we can draw on a long tradition of quantum physics education research in science education: learning difficulties have been researched [14,15], teaching sequences on quantum physics for different target groups have been designed and evaluated [16–19] and novel experiments for laboratory courses have been developed [13,20]. Against the backdrop of

- the relevance of quantum physics education within science education research on the one hand, and
- given the upcoming tasks in teaching modern quantum technologies to a broad audience on the other hand,

It appears essential to create an overview of up-to-now research output in the field of quantum physics education. While the review article by Krijtenburg et al. [14] provides a comprehensive overview of learning difficulties, test instruments, and teaching strategies on quantum physics focusing on secondary and lower elementary levels, Singh and Marshman [15] conducted a systematic literature review into misconceptions of upper-level undergraduate students. However, we identify a research gap regarding an up-to-date survey of the field's scientific output, which is neither restricted to a particular subdomain (e.g., learning difficulties) nor to a specific type of research (e.g., empirical studies). With the study presented in this article, we contribute to closing this gap. For this purpose, we refrain from a detailed content analysis of the field of quantum physics education research, which has already been provided by the review articles mentioned above. Instead, we approach the output of the scientific community in the field of quantum physics education research from an overarching, namely bibliometric, perspective for the period from 2000 to 2021, because previous research stated that bibliometric studies complement existing meta-analyses or systematic literature reviews when it comes to the scientific evaluation of research in a given field [21]. In light of this, we pose the following research questions:

1. How has the scientific output in terms of research publications and citations of articles on quantum physics education has developed over time from 2000 to 2021 in science education research?
2. Who are the most active authors and countries publishing articles on quantum physics education research from 2000 to 2021?
3. What are the most relevant publishing venues in science education research through which the results on quantum physics education are disseminated from 2000 to 2021 and which are the most cited articles?
4. Can a broad collaboration among researchers and countries in quantum physics education research be observed?
5. What are the most relevant keywords, and which co-occurrence patterns exist in articles on quantum physics education research?

The article is structured as follows: in the next section, we describe the methods and data sources used to answer the research questions starting with brief background information on bibliometric analysis. Results of our study are presented in Section 3, and we provide a conclusion in Section 4. Thereby, we also argue as to how the results of this study may inform future quantum physics education research, especially with regards to European efforts.

2. Methods

Bibliometric analysis has gained popularity in science education research in recent years: The scientific output on topics such as physics problem solving [22], STEAM education [23], digital literacy in higher education [24], scientific literacy [25], the role of virtual reality in computer science education [21] or the linking behaviour in the physics education research co-authorship network [26] were—among others—analysed bibliometrically. That is the case because bibliometric analysis is helpful for (a) uncovering and mapping cumulative scientific research foci and (b) producing a thorough overview of scientific output and its development over time in the research area under investigation [27].

In bibliometric studies, quantitative techniques (e.g., co-word analysis) are applied to bibliometric data [28]. Thanks to scientific databases, access to large volumes of bibliometric data is possible in a targeted and straightforward way. Hence, the data that may be included in bibliometric analysis "tends to be massive (e.g., hundreds, if not thousands) and objective in nature (e.g., number of citations and publications, occurences of keywords and topics)" ([27], p. 285).

When planning our bibliometric study to reveal the structure of the research field on quantum physics education in the period from 2000 to 2021, several decisions had to be made. Thus, to clarify our research questions (cf. Section 1), we adapted a workflow recommended by Aria and Cuccurullo [29]:

1. Study design: Definition of research questions and database selection.
2. Data collection: Search query and data export.
3. Data analysis: Decision on bibliometric methods that can be used to clarify the research questions and selection of software to conduct the data analysis.
4. Data visualisation: Selection of visualisation method and appropriate mapping software.
5. Interpretation: Interpretation of bibliometric analysis' results.

In the following, we address the aspects 1. to 4. one by one, whereas our findings are presented in Section 3. We interprete and discuss these findings in the last Section 4.

2.1. Study Design

We have already presented our research questions in the previous section (cf. Section 1). We obtained bibliometric data from two databases, namely Scopus (http://www.scopus.com, accessed on 29 October 2021) and the Web of Science (https://www.webofscience.com/wos/woscc/basic-search, accessed on 29 October 2021). Both databases have been used as sources for bibliometric data in previous studies and are among the most essential bibliographic databases [30]. Regarding research on quantum physics education, these two databases complement one another so that completeness of the dataset used for bibliometric analysis is ensured in the best possible way. The inclusion of journals indexed in the ERIC (https://eric.ed.gov/, accessed on 29 October 2021) database was considered at this stage of our study. However, this only resulted in a large number of duplicates in our sample and no new input was generated for the analysis.

2.2. Data Collection

The data collection was carried out in August and September 2021. For the search query, a set of common criteria for the data was defined for both databases. These include the same search keywords used in combination with binary operators such as *OR* and *AND*. We selected three keywords (*quantum physics*, *quantum mechanics*, *quantum*) for our literature collection which we filtered article titles, article abstracts and the authors' keywords for. Furthermore, we limited our data collection to research published between 2000 and 2021 and in additon, only bibliographic data from articles published in peer-reviewed journals were considered for our bibliometric analysis. We did not restrict our data collection in terms of article language. An overview of the concrete data search procedures and obtained amount of data for both databases is provided in Table 1.

The data from Scopus and Web of Science databases were exported in BibTex format and merged into one dataset using the R-package *bibliometrix* [29]. After removing 90 duplicates, the bibliographic data of 1520 articles on quantum physics education research from 2000 to 2021 remained for the bibliometric analysis. In Table 2, we provide an overview of the data used for our bibliometric analysis.

Table 1. Search queries and the search outcome (number of documents found). The abbreviations in the search queries are those specified by the databases which we refer to here.

Database	**Search Query**	**Refinements**	**Outcome**
Scopus	SRCTITLE((physics OR science) AND education) AND SRCTYPE(j) AND (PUBYEAR > 1999 AND PUBYEAR < 2022) AND (TITLE-ABS-KEY("quantum physics") OR TITLE-ABS-KEY("mechanics") OR TITLE-ABS-KEY("quantum"))	-	231 documents
Web of Science	(TS = (physics) OR TS = (science)) AND TS = (education) AND PY = (2000–2021) AND TI = ("quantum physics") OR TI = ("quantum mechanics") OR TI = ("quantum") OR AB = ("quantum physics") OR AB = ("quantum mechanics") OR AB = ("quantum") OR AK = ("quantum physics") OR AK = ("quantum mechanics") OR AK = ("quantum")	Restriction to articles published in journals and to the research area *Education Educational Research*	1379 documents

Table 2. Overview of the data extracted from Scopus and World of Science databases and used for the bibliometric analysis.

Rubric	**Summary**
Main information about data	
Timespan	2000–2021
Number of sources	44
Number of documents	1520
Average years from publication	8.71
Average citations per document	9.70
Average citations per year per document	0.93
Total number of references (without duplicates)	24,497
Total number of author keywords	1660
Authors	
Number of authors	2607
Number of authors of single-authored documents	422
Number of authors of multi-authored documents	2185
Authors collaboration	
Number of single-authored documents	540
Authors per document	1.72
Co-authors per document	2.24

2.3. Data Analysis and Visualisation

Bibliometric analysis comprises two main techniques: (a) performance analysis and (b) science mapping [27]. Performance analysis aims to assess the scientific outcome in a given research area through quality (e.g., average number of citations per article) and quantity indicators (e.g., the total number of publications), regarding the scientific community in general and different researchers in particular [31]. Science mapping provides a spatial representation of the links between different subject areas, documents or authors for a given research field [32]. Using techniques such as citation analysis [33], co-citation analysis and bibliographic coupling [34], co-word analysis [35] or co-authorship analysis [36], sience mapping "is focused on monitoring a scientific field" ([30], p. 1383). In the study presented in this article, we used both performance analysis and science mapping methods to clarify the research questions. While the analysis regarding research questions 1 to 3 provides a rather descriptive overview of the scientific output in the field of quantum physics education research in a first step, we use the results (and especially those regarding research questions 4 and 5) to derive options that could be worth taking into account for the development of quantum physics education research in the future (cf. Section 4). Table 3 provides a detailed overview of the data analysis carried out.

Table 3. Overview of the data analysis carried out to answer the research questions (cf. Section 1).

Research Question	**Main Technique (*Concrete Analysis*)**
1. How has the scientific output in terms of research publications and citations of articles on quantum physics education has developed over time from 2000 to 2021 in science education research?	Performance analysis (e.g., *analysis of (a) the number of articles published per year and (b) the number of average article citations per year*)
2. Who are the most active authors and countries publishing articles on quantum physics education research from 2000 to 2021?	Performance analysis (e.g., *identification of (a) the most productive authors inlcuding their scientific production over time and (b) the most productive countries*)
3. What are the most relevant publishing venues in science education research through which the results on quantum physics education are disseminated from 2000 to 2021 and which are the most cited articles?	Performance analysis (e.g., *identification of (a) the articles most cited and (b) the most relevant sources in terms of the number of published articles and their temporal development*)
4. Can a broad collaboration among researchers and countries in quantum physics education research be observed?	Science mapping (e.g., *co-authorship analysis*)
5. What are the most relevant keywords, and which co-occurrence patterns exist in articles on quantum physics education research?	Science mapping (e.g., *co-word analysis*)

To perform our bibliometric analysis, we used the R package *bibliometrix* [29] in version 3.1.4. In addition to this R package, we also used the package *ggplot2* in version 3.3.5 to visualize the performance analysis results. For the visualisation of science mapping results, we used VOSviewer software [37] in version 1.6.17, because it “addresses the graphical representation of bibliometric maps and is especially useful for displaying large bibliometric maps in an easy-to-interpret manner” ([29], p. 962).

2.4. Limitations

The research methodology used in this study has some limitations that need to be considered when assessing the results:

1. The numbers of published papers (e.g., by author or country) on quantum physics education reported in this article only refer to the bibliographic data documented in Scopus and Web of Science, respectively. Reported values should therefore not be considered as fixed. The latter holds especially true for the exact number of citations, since not necessarily all citations of a given article are recorded in the databases. In this way, orders for the most frequently cited articles or authors could deviate from reality or articles or authors could even be missing unfairly in such orders. However, we argue that the relevance of this limitation is restricted by the well-justified data collection (cf. Section 2) based on two of the most relevant databases, Scopus and Web of Science.
2. Some authors do not publish many scientific articles but are instead active in important projects or initiatives, for example, or have a strong influence on the research field in other ways. This cannot be taken into account in bibliometric studies.
3. In this study, we only focused on articles published in scientific journals so that future studies can also consider other sources, e.g., books or conference proceedings.
4. In our analysis, we investigated the number of citations for the articles included in our database. Although the role of self-citations in scientific communication has previously been analyzed across disciplines [38], there is an ongoing debate “on

the principles of the role of author-self citation", and "there is no real consensus concerning how this type of self-citations should be defined operatively" ([39], p. 64). We did not specifically analyze self-citations in the field of quantum physics education research in this study but this could be of interest for further research.

5. Altmetrics are social web metrics for published articles that are increasingly used as estimates of publications' impact, cf. [40]. They are not considered in this study. However, this could be a starting point for further research.

3. Results

3.1. Development of the Scientific Output on Quantum Physics Education Research

Research question 1 was: How has the scientific output in terms of research publications and citations of articles on quantum physics education has developed over time from 2000 to 2021 in science education research?

Only about 36.8% (559 out of 1520) of the articles in our dataset were published in the period up to 2010. The number of publications on quantum physics education research increased from 31 in 2000 to 118 in 2020 with an annual growth rate of about 6.9% (cf. Figure 1).

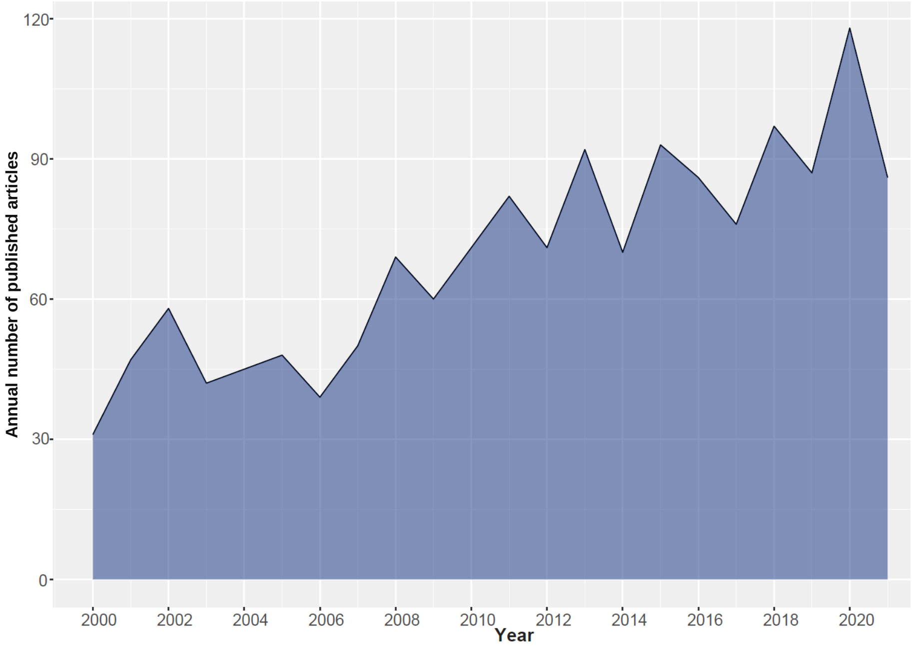

Figure 1. Annual number of articles on quantum physics education research published in Scopus or Web of Science indexed journals from 2000 to 2021.

On average, each of the published articles was cited 9.70 times in total. The average number of citations per year for each publication was around 0.93. Figure 2 shows the average article citations per year.

Out of 2607 authors included in the collection, 396 published at least two articles on quantum physics education research between 2000 and 2021 documented in either Scopus or Web of Science. Furthermore, 126 authors published at least three, 58 at least four, and 36 authors published five or more articles. In the next section, we will focus on the latter, namely the most active authors (and countries) publishing articles on quantum physics education.

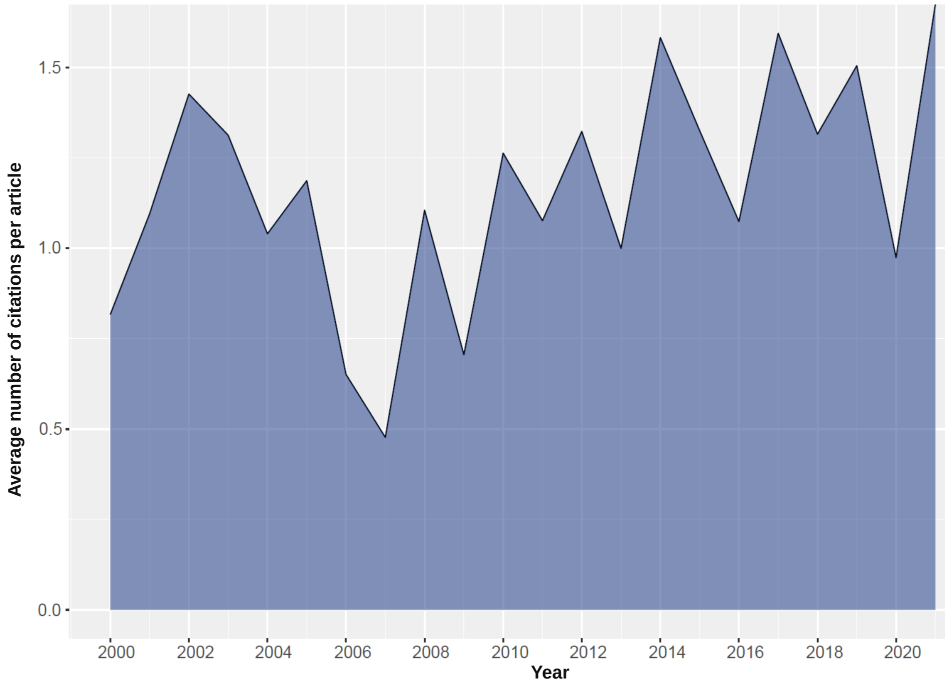

Figure 2. Average number of citations per article and per year.

3.2. Most Active Authors and Countries Publishing Articles on Quantum Physics Education Research

Research question 2 was: Who are the most active authors and countries publishing articles on quantum physics education research from 2000 to 2021?

Table 4 lists the ten most productive authors in the quantum physics education research area in terms of articles published between 2000 and 2021.

Table 4. Most productive authors including number of published articles on quantum physics education research. It is noteworthy that this ranking can only take into account articles that are documented in the Scopus and Web of Science databases.

Most Productive Authors	# Articles
1. Singh, C.	33
2. Marshman, E.	16
3. Robinett, R.	14
4. Marsiglio, F.	13
5. Belloni, M.	8
6. Kohnle, A.	8
7. Passante, G.	8
8. Shaffer, P.	8
9. Shegelski, M.	8
10. Emigh, P.	7

While some of the most productive authors have consistently contributed to the field with publications over the last two decades, others published all their work within a shorter period of time, mainly after 2014 (cf. Figure 3).

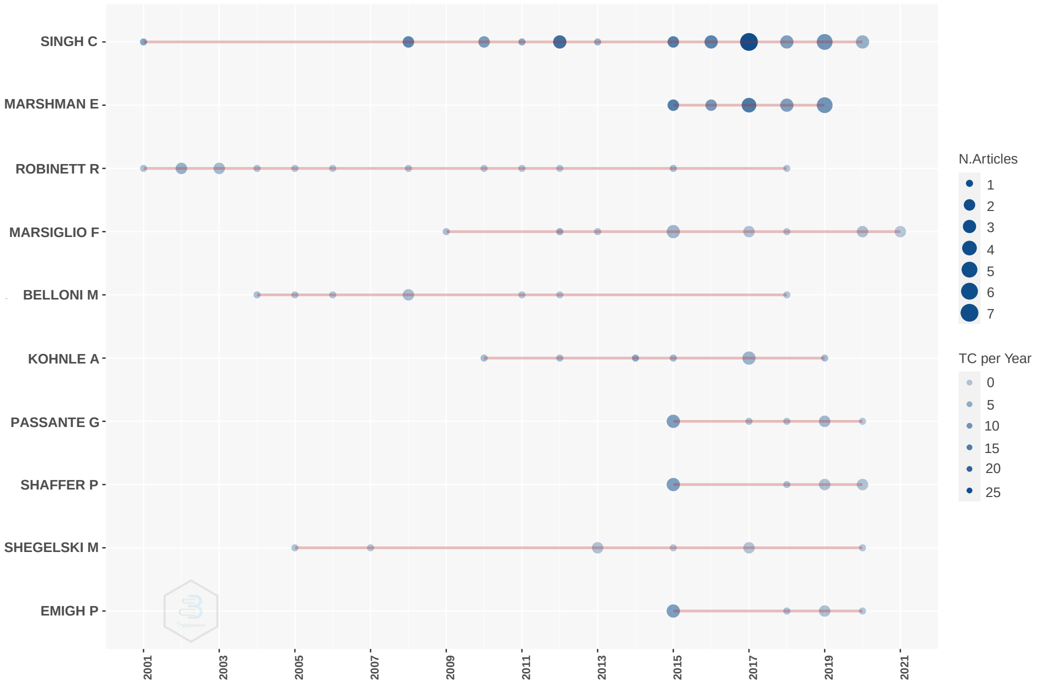

Figure 3. Top authors' production over the time in terms of published articles including the annual number of published articles (N. Articles) and the total number of citations (TC) per year.

To provide an overview of the countries participating in the scientific debate on quantum physics education research, we investigated the corresponding authors' countries as well as the number of single and multiple country publications (cf. Figure 4).

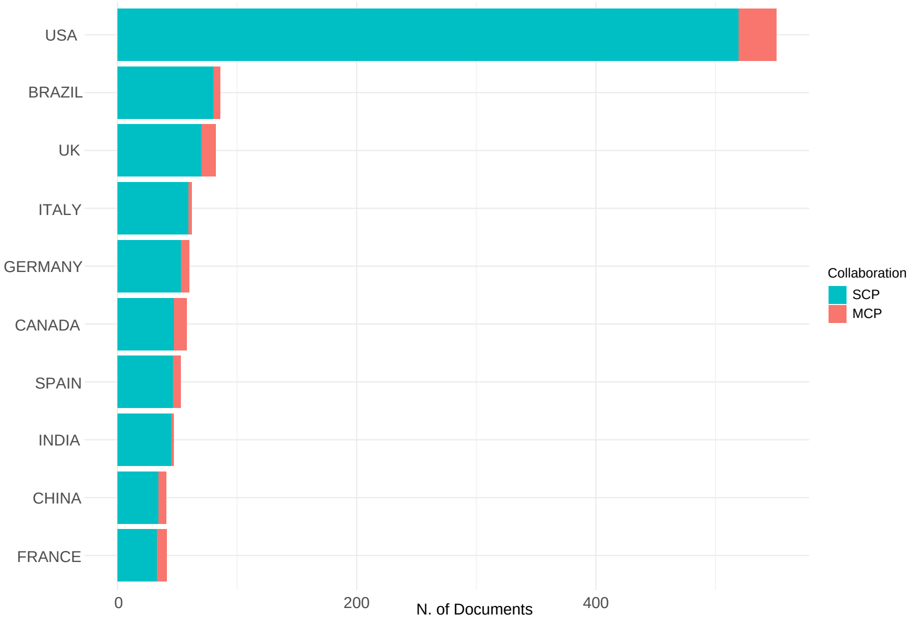

Figure 4. Number of country articles including the ratio of single country publications (SCP) and multiple country publications (MCP).

Of the ten countries with the most publications on quantum physics education research, five are from Europe (UK: 82 publications, Italy: 62, Germany: 60, Spain: 53 and France: 41). More than one third (551 out of 1520) of the publications analyzed were written by a corresponding author from the USA. Thereby, the ratio of multiple country publications was only 5.8%. In contrast, France has the most significant percentage of multiple country publications (19.5%), followed by Canada (19.0%) and China (17.1%). Figure 4 provides a graphical overview of the results for the ten most productive countries.

3.3. Most Relevant Journals and Most Cited Articels on Quantum Physics Education

Research question 3 was: What are the most relevant publishing venues in science education research through which the results on quantum physics education are disseminated from 2000 to 2021 and which are the most cited articles?

Most articles on quantum physics education in the period from 2000 to 2021 were published in the *American Journal of Physics* (477 articles), closely followed by the *European Journal of Physics* (465 articles). Thus, more than 60% of the articles in our dataset were published in one of these two journals. An overview of the top ten most relevant sources in terms of published articles is given in Table 5.

Table 5. The most relevant sources in terms of the number of published articles on quantum physics education research. Only journals that publish articles in the English language are included here.

Most Relevant Sources	# Articles
1. American Journal of Physics	477
2. European Journal of Physics	465
3. Journal of Chemical Education	231
4. Physical Review (ST) Physics Education Research	72
5. Physics Education	57
6. Science & Education	40
7. Chemistry Education Research and Practice	22
8. International Journal of Science Education	12
9. The Physics Teacher	9
10. International Journal of Mathematical Education in Science and Technology	7

Among the journals with the most published articles on quantum physics education we also find the *Revista Brasileira de Ensino de Fisica* (53 published articles), a journal that does not publish in the English language. While the *American Journal of Physics* continuously published many articles on quantum physics education research over the entire observation period, the number of articles in the *European Journal of Physics* increased significantly, especially in the years after 2010. In Figure 5, the cumulative number of documents published annually on quantum physics education research is presented for the seven publishing venues with the most quantum physics education related articles.

The massive impact of the *American Journal of Physics* on the field of quantum physics education research is not only reflected in the number of articles published but also in the number of top manuscripts per citations: Nine of the ten most frequently cited papers in the field were published in the *American Journal of Physics*, cf. Table 6.

It is noteworthy that the list in Table 6 also includes citations from outside the research field under investigation, namely quantum physics education research. Hence, in order to extract the most influential publications for the quantum physics education research community, we investigated how many times a given article included in our dataset has been cited by other authors of the same collection. This is referred to as the number of local citations. The ten articles with the most local citations are shown in Table 7: Again, nine out of those ten papers appeared in the *American Journal of Physics*.

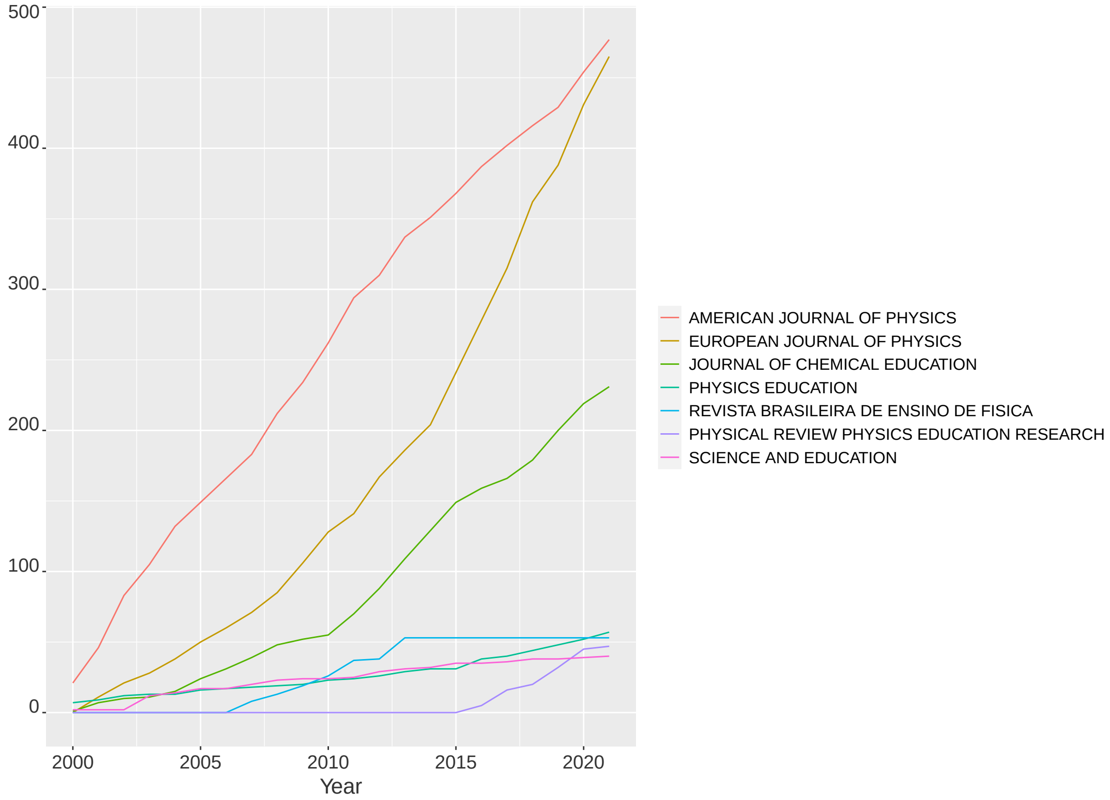

Figure 5. Cumulative number of documents published annually on quantum physics education research for the seven sources with the most published articles on quantum physics education research in total.

Table 6. Most cited manuscripts (top ten, published between 2000 and 2021) in the field of quantum physics education research. Besides the corresponding authors, the publication year, the journal title, the total number of citations (TC) and the total number of citations per year are shown. A reference for all the most cited articles is provided in the last column.

Corresponding Author	Publication Year	Journal	TC	TC/Year	Reference
Bender, C.M.	2003	Am. J. Phys.	268	14.11	[41]
Novotny, L.	2010	Am. J. Phys.	233	19.42	[42]
Bonneau, G.	2001	Am. J. Phys.	170	8.10	[43]
Griffiths, D.J.	2001	Am. J. Phys.	158	7.52	[44]
Brun, T.A.	2002	Am. J. Phys.	158	7.90	[45]
Bender, C.M.	2013	Am. J. Phys.	149	16.56	[46]
Boatman, E.M.	2005	J. Chem. Educ.	149	8.76	[47]
Singh, C.	2001	Am. J. Phys.	148	7.05	[48]
Case, W.B.	2008	Am. J. Phys.	137	9.79	[49]
Laloë, F.	2001	Am. J. Phys.	129	6.14	[50]

Table 7. Most local cited manuscripts (top ten, published between 2000 and 2021) in the field of quantum physics education research. Besides the corresponding authors, the publication year, the journal title, the total number of local citations (LCS) and the total number of global citations (GCS) are shown. A reference for all the most cited articles is provided in the last column.

Corresponding Author	Publication Year	Journal	LCS	GCS	Reference
Singh, C.	2001	Am. J. Phys.	38	148	[48]
Müller, R.	2002	Am. J. Phys.	31	101	[18]
Singh, C.	2008	Am. J. Phys.	28	104	[51]
Galvez, E.J.	2005	Am. J. Phys.	27	63	[52]
Kohnle, A.	2014	Eur. J. Phys.	25	46	[53]
Wittmann, M.C.	2002	Am. J. Phys.	24	88	[54]
Dehlinger, D.	2002	Am. J. Phys.	22	85	[55]
Zollman, D.A.	2002	Am. J. Phys.	23	96	[56]
Singh, C.	2008	Am. J. Phys.	22	85	[57]
Cataloglu, E.	2002	Am. J. Phys.	21	78	[58]

3.4. Collaborations among Researchers and Countries in Quantum Physics Education Research

Research question 4 was: Can a broad collaboration among researchers and countries in quantum physics education research be observed?

Although collaborations between scientists can manifest themselves in diverse ways, and collaborations will not always be associated with co-authored papers [59], the number of joint publications may serve as a measure of collaboration between scholars [60]. Therefore, we conducted a co-authorship analysis to investigate whether there is broad collaboration between researchers in the quantum physics education research community. For network visualisation, we used VOSviewer software [37]: Each node in Figure 6 represents one author. The node size scales with the number of articles published (referred to as *weight*) by the corresponding author. The lines between two nodes (i.e., two authors) stands for co-authored articles of these authors, whereas the line thickness scales with the number of co-authored articles. The colors represent clusters, i.e., collaborations among at least two researchers with joint publications.

Figure 6 indicates several (predominantly) disjoint clusters, each comprising only a few authors. On the one hand, this shows it is true that there are some collaborations among scholars on quantum physics education research. On the other hand, only a few of these groups are networking with each other—at least with regard to joint publications. A more precise analysis of the individual clusters also shows that they predominantly comprise authors from the same country (cf. Table 8). This points to the fact that there have only been a few international collaborations in the scientific community on quantum physics education research up to now. The latter is supported by Figure 7, which displays co-authorship analysis results based on countries.

As a side note, it is worth mentioning that various programmes around the world serve to network the actors in the field these days: for example, within the European Quantum Flagship (https://qt.eu/, accessed on 28 October 2021) an area dedicated to *Education & Training* has been established. In the future, this is likely to increase international collaborations in quantum physics education research, which should also be reflected in an increase of the number of co-authored articles.

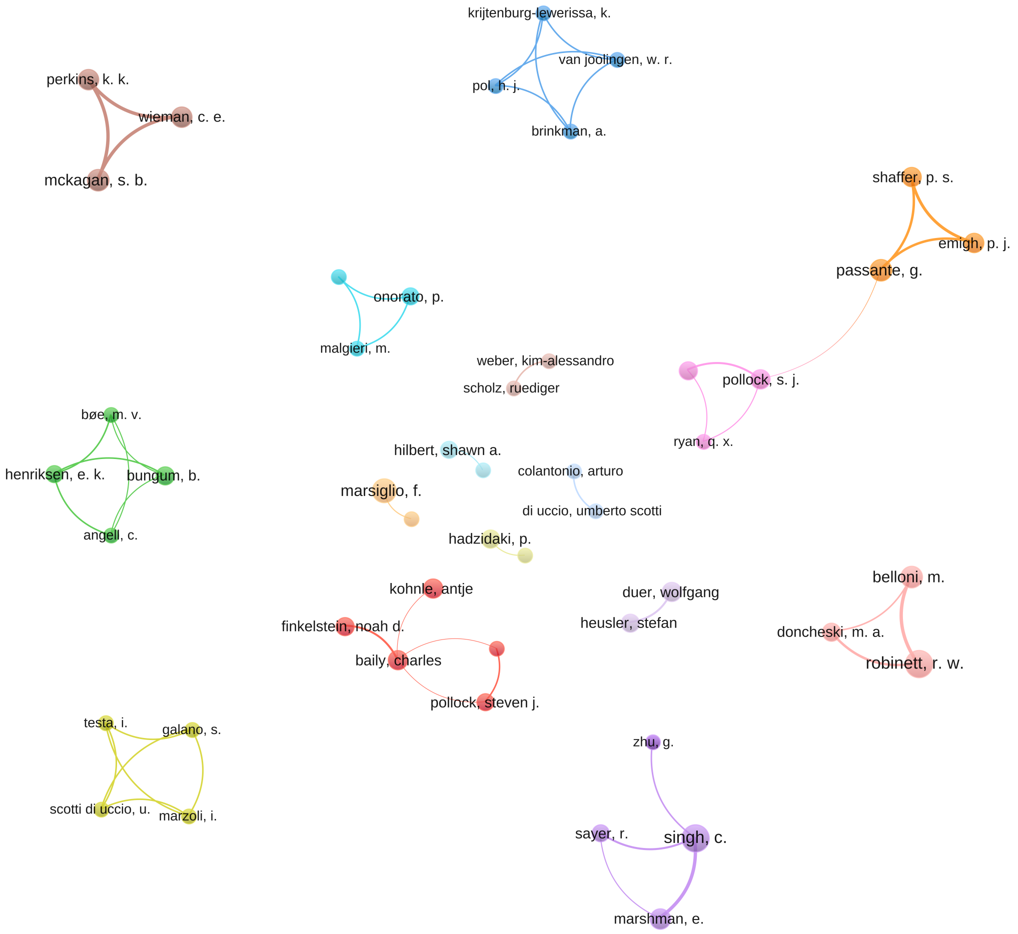

Figure 6. Co-authorship network focusing on authors of quantum physics education research articles from 2000 to 2021. Authors with at least three publications have been included (126 authors). Authors who have only published single-authored publications are surpressed in the visualisation. We used LinLog as VOS layout technique, and the modularity technique for clustering. For details on these techniques see [61–63].

Table 8. Exemplary national and international collaborations (incomplete) identified by co-authorship analysis (cf. Figure 6).

Cluster	Researchers and Countries	Exemplary Publication(s)
Brown	Perkins, Wieman, McKagan (USA)	[64]
Blue	Krijtenburg-Lewerissa, Pol, Brinkman, van Joolingen (The Netherlands)	[65]
Orange	Emigh, Passante, Shaffer (USA)	[66]
Light red	Belloni, Doncheski, Robinett (USA)	[67–69]
Dark Purple	Singh, Marshman, Zhu, Sayer (USA)	[70,71]
Yellow	di Uccio, Colantonio, Galano, Marzoli, Trani, Testa (Italy)	[72,73]
Green	Bøe, Henriksen, Bungum, Angell (Norway)	[74,75]
Turquoise	Malgieri, Onorato, De Ambrosis (Italy)	[17]
Red	Baily, Finkelstein, Pollock (USA), Kohnle (UK)	[76,77]
Light purple	Dür (Austria), Heusler (Germany)	[78,79]

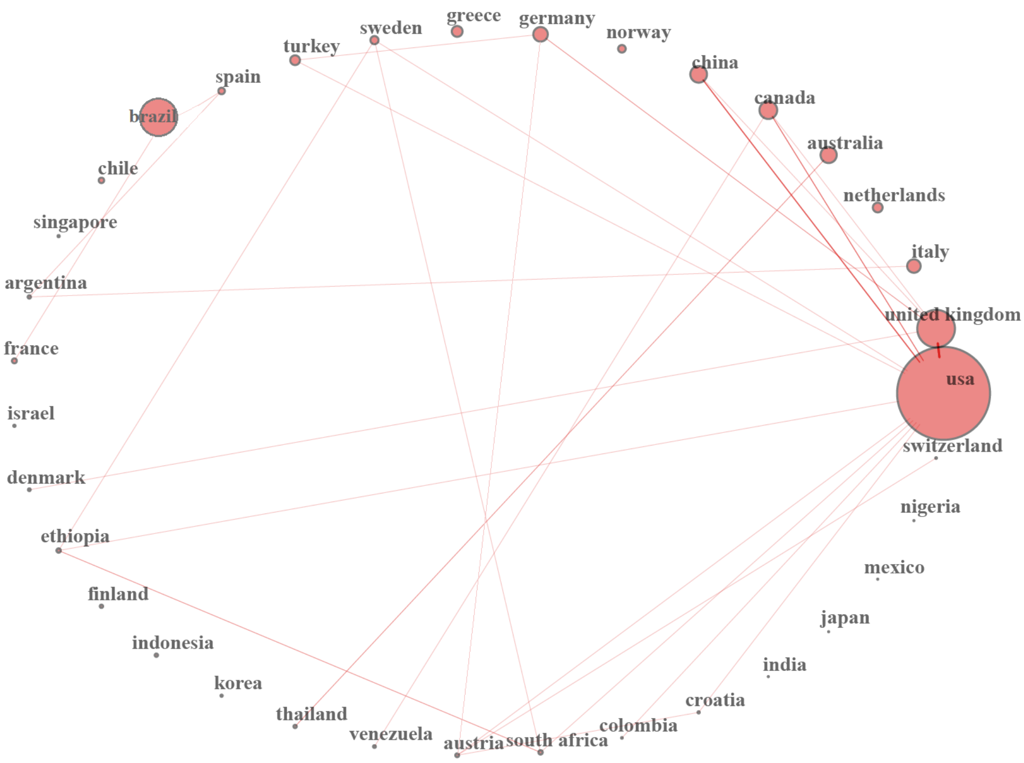

Figure 7. Co-authorship network focusing on authors' countries. Each country node scales with the number of articles on quantum physics education research published between 2000 and 2021. The lines between two nodes (i.e., two countries) stands for co-authored articles of authors from these countries, whereas the line thickness scales with the number of co-authored articles. Compared to Figure 6, a few more international collaborations can be found here. However, it should be noted that Figure 6 only includes authors who have contributed at least three articles to the research area. Here, all countries have been included instead. The results presented in this figure fit well with those presented in Figure 4.

3.5. *Keyword Co-Occurrence Patterns in Quantum Physics Education Research*

Research question 5 was: What are the most relevant keywords, and which co-occurrence patterns exist in articles on quantum physics education research?

A frequency analysis shows that the keyword most frequently given by authors to their articles was *upper-division undergraduate* (139 mentions). This is not surprising, but reflects the large proportion of articles published in the *American Journal of Physics* and the *European Journal of Physics* (cf. Table 5). Other frequently mentioned keywords are *physical chemistry* (111 mentions), *quantum chemistry* (99 mentions) or *quantum mechanics* (78 mentions). Of course, these rather general terms do not allow us to determine the main research topics in the field or their shift over time. Hence, we conducted a co-word analysis (cf. Section 2) to uncover co-occurence patterns which in turn allow deeper insights, since "the co-word analysis is a technique that examines the actual content of the publication itself" ([27], p. 289). Therefore, a co-word analysis is based on the assumption that words "that frequently appear together have a thematic relationship with one another" ([27], p. 289).

We used the VOSviewer software [37] to visualise the results of our co-word analysis: The software first determines a similarity matrix based on a normalised co-occurrence matrix and afterwards constructs a two-dimensional map via the VOS mapping technique such that "the distance between any pair of items i and j reflects their similarity s_{ij} as accurately as possible" ([37], p. 531). Hereby, the similarity s_{ij} is assigned to two words i and j from the data set using the so-called association strength [80], which is calculated via $s_{ij} = \frac{c_{ij}}{w_i w_j}$, with c_{ij} standing for the number of co-occurences of the terms i and j and $w_{i/j}$ meaning the total number of occurences of the terms i and j, respectively [37].

The terms we have included in the co-word analysis are taken from the author keywords and article titles as well as the abstracts in order to be as complete as possible. However, only terms that occured in a minimum of 10 documents were involved (564 terms) for the co-word analysis, and terms with a low relevance score were also excluded. After that, 338 words remained for mapping, whereby we also manually excluded some general terms which we believed to gain no additional content from (e.g., student). The final co-word map is shown in Figure 8.

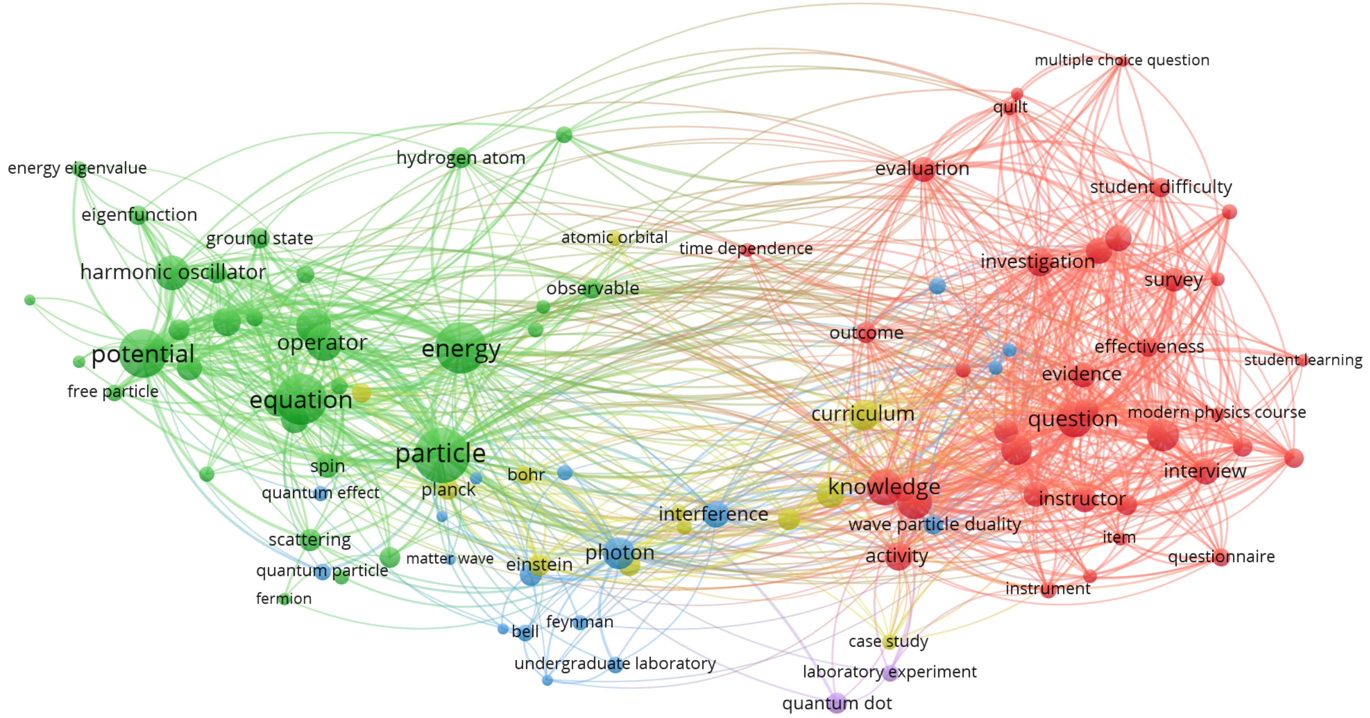

Figure 8. Visualisation of the co-word analysis results. The relative frequency of the occurence of terms is represented by the corresponding font size, and the co-occurrence of keywords is represented by connecting lines. Clusters of repeatedly co-occurring terms are shown in the same color.

The co-word analysis brings up two primary clusters that are by no means disjoint (cf. Figure 8). One cluster (coloured green) includes words such as *particle*, *energy*, *potential*, *harmonic oscillator*, *ground state*, *eigenfunction* to name but a few. There are numerous links between the terms in this cluster and those in the second large cluster (coloured red). This second cluster includes terms such as *student difficulty*, *investigation*, *questionnaire*, *survey*, *effectiveness* and many more. These two clusters can be used to identify two main pillars of quantum physics education research: While one pillar is primarily dedicated to the reconstruction of quantum physics content for teaching (i.e., topic-centered studies), the other pillar focuses on empirical research into teaching and learning quantum physics (i.e., methodological-centered studies). The numerous connections between the two clusters express an interdependence of these two pillars.

Three further (rather small) clusters reflect specific features of quantum physics education research: one cluster (coloured blue) includes terms such as *photon*, *interference*, *bell*, or *undergraduate laboratory* and represents research activities that drive the development of quantum physics experiments and their integration into undergraduate laboratory courses. Another small cluster (coloured purple) with terms like *laboratory experiment* or *quantum dot* is connected to the previous one, and a last cluster (coloured yellow) includes general terms (rather independent from quantum physics), for instance *curriculum*, *knowledge* or physicists' names. Consequently, this cluster is strongly intertwined with all other clusters. This is graphically mirrored in Figure 8.

In order to illustrate the temporal shift of research foci within quantum physics education research, we have finally converted Figure 8 into an overlay format. Therefore, the VOSviewer software uses the publication years of the articles in which a given term appeared [81]: the average publication year of these articles is calculated and the scale of the resulting publication years is linearly transformed to a scale between 0 and 1 (which is coded with colours). For our co-word analysis, the corresponding overlay visualisation is shown in Figure 9.

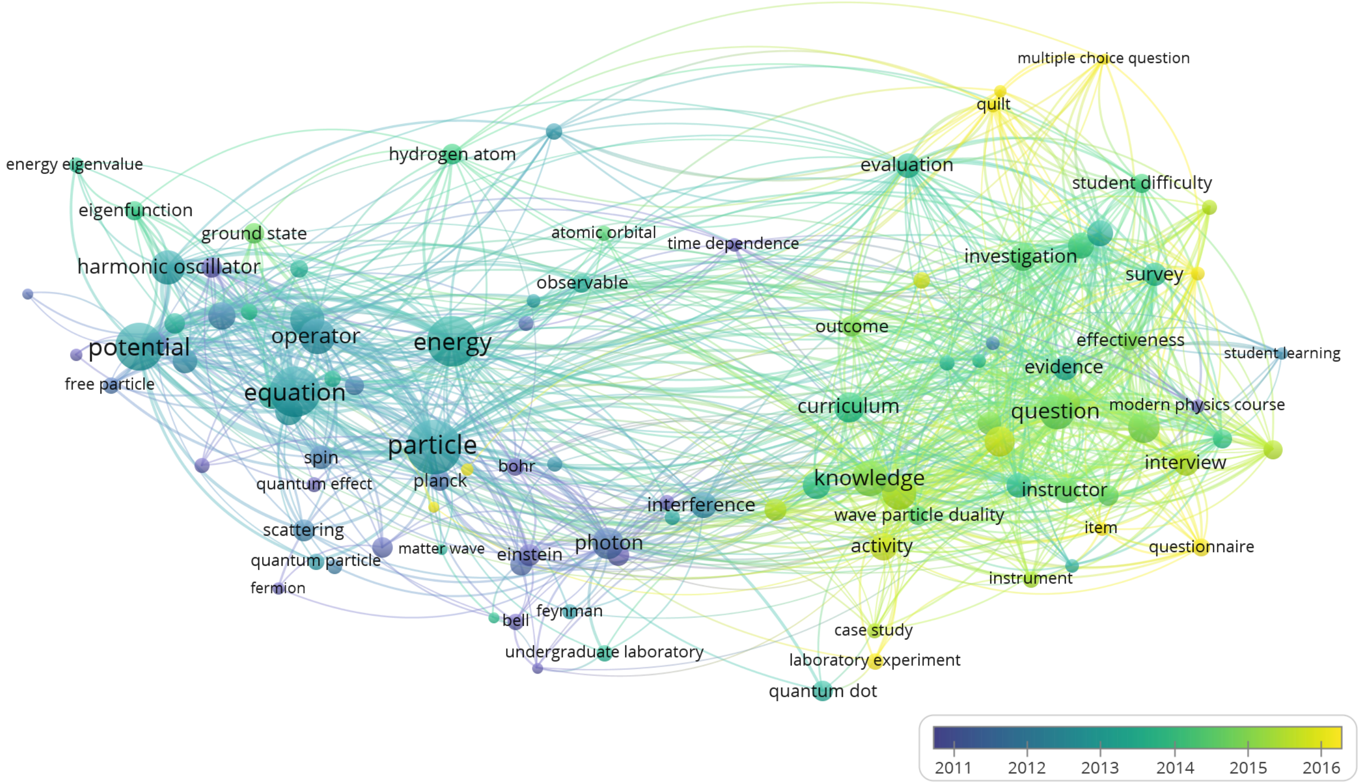

Figure 9. Overlay visualisation of the co-word analysis results. The time scale only ranges from 2011 to 2016, as the overlay visualisation is based on the average publication year of the articles in which a specific term appeared.

Figure 9 indicates a shift in the main focus of research in quantum physics education: while in the past mainly content-related research on quantum physics education was published (left cluster), empirical research on teaching and learning has taken on an increasingly central role in recent years (right cluster). In the next Section 4, we will argue how these observations may inform future quantum physics education research.

4. Discussion and Conclusions

In this article, we reported on the results of a bibliometric analysis of the quantum physics education research field based on 1520 articles published in peer-reviewed journals between 2000 and 2021. For this purpose, we extracted bibliographic data from the two databases Scopus and Web of Science according to specified search criteria. Techniques of performance analysis as well as science mapping were used to address five research questions.

4.1. Discussion of Performance Analysis Results (Research Questions 1–3)

The main results to answer the research questions 1 to 3 are summarized below including a discussion of how these results might influence future developments in the field of quantum physics education research.

- *Main results on research question 1*: The number of published papers on quantum physics education research has increased steadily over the observation period from 31 articles in 2000 to 118 articles in 2020, with an annual growth rate of about 6.9%.
- *Main results on research question 2*: The research on quantum physics education is significantly driven by authors from the USA: more than 1/3 of the documents analysed were published by a corresponding author from the USA. Against this backdrop, it is not surprising that among the top ten most productive authors, seven are from the USA (led by Singh, C.). Furthermore, among the ten leading countries in the research field, five are from Europe (UK, Italy, Germany, Spain and France).
- *Main results on research question 3*: The two journals *American Journal of Physics* and *European Journal of Physics* published the most papers on quantum physics education research and the number of publications in these journals increased more than in all other journals over the observation period. Among the top ten most cited papers on quantum physics education research, nine articles are published in *American Journal of Physics*—the latter is true regardless of whether one analyses global or local citations.

We argue that the results on these three research questions provide hints for future developments of the European quantum physics education research community: compared to the US community, the results of research questions 1 and 2 indicate further potential for the European community with respect to the communication of scientific results on quantum physics education research in indexed journals. The *American Journal of Physics*, a journal published in the USA, is the most important publication venue in the field as can be derived from the results on research question 3. Therefore, we argue that in the future, running special issues on quantum physics education research in European journals could stimulate the communication of research results from European actors and is thus likely to contribute to closing the gap to the USA in the field under investigation.

4.2. Discussion of Science Mapping Results (Research Questions 4 and 5)

As in the previous section, the main results to answer the research questions 4 and 5 are summarized including a discussion of how these results might influence future developments in the field of quantum physics education research.

- *Main results on research question 4*: The scientific community engaged with quantum physics education research has not formed well-established (international) collaborations yet. Instead, the community is characterised by several smaller and predominantly national collaborations (cf. research question 4).

We believe that the co-authorship analysis results (cf. Figures 6 and 7) may be important for the community, showing that their is a necessity for stronger (cross-national) collaboration in order to improve the field. We have already indicated that there are several initiatives driving this process, e.g., within the European Quantum Flagship.

However, our observation is consistent with previous research that focused on the dynamics of collaboration networks: Anderson et al. showed that in the case of a young research field “islands of individual researchers labored in relative isolation, and the coauthorship network was disconnected” ([26], p. 1), whereas decades later, “rather than a cluster of individuals, we find a true collaborative community, bound together by a robust collaboration network” ([26], p. 1). Thereby, the development would not be progressive, but would be influenced by fundamental structural changes, e.g., “the introduction of institutions such as field-specific conferences and journals” ([26], p. 1). This is congruent with our suggestion regarding the above results for research questions 1 to 3: Following the findings of Anderson et al. [26], special journal issues devoted to quantum physics education research, or even science education journals dedicated to quantum physics education could boost the field’s dynamics in terms of collaboration networks.

- *Main results on research question 5*: Quantum physics education research comprises two main areas, as a co-word analysis revealed. On the one hand, quantum physics education research is dedicated to reconstructing quantum physics content for teaching; on the other hand, it focuses on empirical research into learning and teaching quantum physics. These two pillars are by no means disconnected, but rather interconnected and are complemented by smaller research areas that primarily focus on quantum physics experiments for laboratory courses. During the observation period, a shift in the research focus from more content-specific work to empirical studies on the teaching and learning of quantum physics can be observed.

Against the backdrop of the co-word analysis results (cf. Figure 8), we would finally like to return to the beginning of the article (cf. Section 1): in the introduction, we outlined the increasing importance of the quantum technologies 2.0. We showed that quantum physics education research can and must make contributions to raise awareness and acceptance of quantum technologies in society. Therefore, the targeted development of training programmes and outreach activities seems necessary. This requires empirical research on teaching and learning quantum physics on the one hand. However, quantum technologies as a context may lead to a shift of paradigms in the teaching of quantum concepts on the other hand, especially with regards to high school students, workforce or general public. For instance, a qualitative understanding of the basic concepts is sufficient for learning about quantum technologies, while deeper insights into the mathematical formalism are not necessarily required for this purpose. Consider, for example, quantum algorithms, which can be described with qubits and gates without detailed knowledge of the physical realisation [82]. Hence, quantum technologies 2.0 offer numerous research opportunities in the future that are not yet covered by the map of (key-)word co-occurrences (cf. Figure 8), which mirrors that issues related to modern quantum technologies have not been in the focus of quantum physics education researchers so far. However, our findings may lead to new research foci in the scientific landscape of quantum physics education research in the future, e.g., by combining topic- and methodological-centered studies in order to open up quantum technologies 2.0 for educational purposes.

Further interpretation of the co-word analysis results reveals another eye-catching aspect (cf. figure 8): among the most often occurring keywords there are none that would indicate broad usage of augmented (AR) and virtual reality (VR) in the quantum physics context yet. Given the importance of AR/VR for science education [83,84], this seems surprising. However, we believe that AR/VR environments offer further potential for optimizing the teaching and learning of quantum physics in the future: Learning quantum physics is difficult, not least because of its abstract nature, and hence, AR/VR could be used to “visualize the invisible” [85]. Consequently, we believe that strengthening research efforts concerning AR/VR in quantum physics education in the future could add value to the field.

In conclusion, we remark that with respect to the research questions, the results of our study may contribute to future developments in the field under investigation and may thus influence research practices in the field of quantum physics education in the future: both in terms of research foci and the infrastructures of the research community, as discussed in this Section 4.

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